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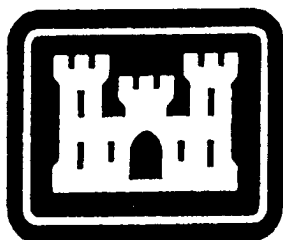
CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Destruction of Asbestos-Containing Materials Using
Plasma Arc Technology

by

Hany H. Zaghloul, Louis J. Circeo, Robert A. Newsom,
Edgar D. Smith, and Stephen W. Maloney

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13. ABSTRACT (Maximum 200 words) The proper control of asbestos-containing material (ACM) is a top priority of the Department of Defense (DOD). The DOD has control or responsibility for a large quantity of property, the majority of which has some level of asbestos management problems. Plasma arc technology destruction of ACM can be an effective, economical, and timely solution to the asbestos disposal problem. The very high temperatures achievable with plasma arc torches can convert asbestos and ACM into a chemically inert glasslike residue that meets all Federal (EPA) and local regulatory compliance. The development of this emerging technology for the destruction of ACM is an important and desirable step toward construction and testing of a basic prototype system. This study tested and evaluated concepts for the vitrification and destruction of ACM taken directly from asbestos abatement project sites. Results of the Construction Productivity Advancement Research (CPAR) test program indicated that plasma arc technology would successfully process pure asbestos and ACM into a safe and harmless vitrified product. The study also addressed the design criteria for a mobile Plasma Pyrolysis System (PAPS) for on-site destruction of ACM, including a time schedule to develop and test an industrial-scale prototype system.				
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Foreword

This study was conducted for the Directorate of Research and Development, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under "Construction Productivity Advancement Research" (CPAR) Work Unit "Destruction of Asbestos-Containing Waste Materials"; Funding Authorization Document (FAD) 92-0804076, dated 21 February 1992. The technical monitor was Jerry Dause, CEMP-RT.

The work was performed by the Industrial Operations Division (UL-I) of the Utilities and Industrial Operations Laboratory (UL), U.S. Army Construction Engineering Research Laboratories (USACERL). Other organizations participating in this joint research/effort were: (1) the *Construction Research Center (CRC)* and the *Georgia Tech Research Institute (GTRI)*, Georgia Institute of Technology, Atlanta, GA, which was responsible for the program and technical management; (2) *Plasma Energy Corporation (PEC)*, Raleigh, NC, which provided plasma torch systems and guidance for operation and setup of the systems, assisted in maintaining the plasma heating systems, and acted as a consultant to troubleshoot system operating problems; (3) *Plasma Technology Corporation (PTC)*, Raleigh, NC, which provided guidance and support during the experimental testing program; and (4) *Winter Environmental Services, Inc (WESI)* (formerly *Asbestos Abatement Technology*), Atlanta, GA, which was responsible for all aspects of the research program related to the obtaining, handling, safety, and disposal of the ACM from their asbestos abatement building sites. Dr. Louis Circeo and Robert Newsom are associated with Georgia Institute of Technology, Atlanta, GA. Dr. Edgar D. Smith was the USACERL principal investigator and technical point of contact. Hany Zaghloul was the USACERL technical consultant. Walter J. Mikucki is Chief, CECER-UL-I; John T. Bandy is Operations Chief, CECER-UL; and Gary W. Schanche, CECER-UL, is the associated Technical Director. The USACERL technical editor was William J. Wolfe, Technical Resources.

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1 Introduction

Background

Asbestos remediation and disposal in the United States is a multi-million dollar industry. Over 750,000 public, commercial, and industrial buildings have been estimated by the U.S. Environmental Protection Agency (USEPA) to have asbestos-containing materials (ACM). During the renovation, reconstruction, or demolition of these facilities or when the contamination levels become too high, extensive procedures are required to safely handle the ACM. These rehabilitation programs are expensive and a significant cost burden for the country.

The proper procedures and control of the ACM is a top priority of the Department of Defense (DOD). Since 1984, over \$5 million has been spent to correct or control the asbestos in the Pentagon building alone. The DOD has control or responsibility for a large quantity of property, both nationally and internationally. A large majority of these facilities have asbestos management problems that range from simple to extensive. Under the Asbestos Emergency Response Act of 1986 (AHERA), all school grades kindergarten through twelve are mandated to be inspected. The extension to all public and commercial buildings is also being considered by the AHERA. Procedures and the proper steps for handling the ACM are specified by legislation. Dealing with the asbestos problem for both the DOD and the U.S. construction industry is expected to continue for many years into the future.

As the number of available landfills decrease due to restrictions specified by the USEPA and to the need to comply with the National Emission Standards for Hazardous Air Pollutants (NESHAP), the cost for asbestos disposal will increase due to a relative increase in demand and also to the greater transportation distances to available landfills. The possible migration of asbestos fibers into the air and groundwater from landfill areas will also add to the cost of disposal due to more restrictive enforcement.

Plasma arc technology destruction of ACM can be an effective, economical, and timely solution to the asbestos disposal problem. The very high temperatures achievable with plasma torches can convert the asbestos and ACM into a chemically inert glasslike residue that meets all Federal (USEPA) and local regulatory compliance.

The development of this emerging technology for the destruction of ACM is an important and desirable step toward construction and testing of a basic prototype system.

Objectives

The overall objectives of this study were to conduct all research necessary to test and evaluate the innovative concepts required for the vitrification and destruction of asbestos-containing materials, taken directly from asbestos abatement project sites. Research was conducted in two phases. Results of the CPAR Phase 1 test program indicated that plasma arc technology would successfully process pure asbestos into a safe and harmless vitrified product. The objectives of the CPAR Phase 2 program were to demonstrate that ACM could also be successfully processed into a harmless vitrified product, and to address the design criteria for a mobile Plasma Asbestos Pyrolysis System (PAPS) for on-site destruction of ACM, including a time schedule to develop and test an industrial-scale prototype system.

Approach

The study was divided into its major experimental and technical components. The experimental approach was to proof all aspects of the asbestos destruction process such as handling, feeding and extraction, operation, and determining the condition of the processed products. In addition, as part of the experimental approach, offgas emissions were tested to verify compliance with all Federal, State, and local regulatory requirements. Consequently, the technical aspects of the approach targeted future process optimization, technology transfer, and economic analysis. An important part of the technical approach was the development, characterization, and production of the PAPS basic design criteria and preliminary design drawings. This effort was based on the entire project results, including findings and conclusions from both the experimental and operational protocols of the plasma-processing unit at Georgia Tech.

Metric Conversion Factors

The following conversions factors are provided for standard units of measure used throughout this report.

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 sq ft	=	0.093 m ²
1 cu ft	=	0.028 m ³
1 cu yd	=	0.7645 m ³
1 mi	=	1.61 km
1 lb	=	0.453 kg
1 gal	=	3.78 L
1 ton	=	0.907 metric ton
°F	=	(°C × 1.8) +32

2 Background

The Asbestos Hazard (2,3,4)

Asbestos is a naturally occurring mineral. It is distinct from other minerals by its crystals, which form long, thin fibers. Deposits of asbestos are found in the United States and throughout the world. The primary sites of commercial production are in Canada, Russia, and South Africa. When extracted from the earth, the asbestos-containing rock is crushed, milled, and graded. This produces long, threadlike fibers of material. What appears as a single fiber is actually an agglomeration of hundreds or thousands of fibers, each of which can be divided even further into millions of microscopic fibrils. Chrysotile is the most common type of asbestos used in buildings, and accounts for approximately 95 percent of the asbestos found in U.S. buildings.

Asbestos was used widely because it was plentiful and inexpensive. Its unique properties (fire resistance, high tensile strength, low thermal and electrical conductivity) made it a popular material throughout the construction industry. Asbestos is routinely mixed with other materials (binders, cement, asphalt, vinyl, etc.) for these applications. Collectively these products are often referred to as asbestos-containing materials, or ACM. Three categories of ACM are normally used in buildings:

- surfacing materials (sprayed or troweled onto surfaces)
- thermal system insulation (pipe wrap, blanket insulation, cements, and muds)
- miscellaneous materials (floor and ceiling tile, roofing felt, concrete pipe, siding, fabrics).

In 1984, over 150,000 metric tons of asbestos were used in the United States. In 1988, the USEPA announced the results of a national asbestos survey of 3.6 million U.S. public and commercial buildings. About 750,000 buildings contained potentially harmful ACM. About 25 percent of the affected buildings have sprayed-on or troweled-on asbestos surfacing material, such as acoustical plaster on ceilings. An estimated 80 percent of these buildings contained asbestos in thermal system insulation (pipes, boilers, tanks, or ducts). The ACM was damaged in approximately 70 percent of these buildings.

Asbestos is a known human carcinogen that can cause several types of cancer. Asbestos can present a health hazard by emitting microscopic fibers when crushed or pulverized. These fibers stay suspended in the air for long periods of time and can become lodged and can accumulate in the lungs. As exposure increases, the risk of disease also increases because the primary health effects from asbestos exposure act on the lungs. No safe threshold of asbestos exposure has been established. The principal diseases directly attributable to asbestos inhalation are:

- *Asbestosis*: A disease characterized by fibrotic scarring of the lung.
- *Lung Cancer*: A fivefold increase in risk can result from asbestos exposure.
- *Mesothelioma*: A cancer of the chest cavity lining or in the lining of the abdominal cavity.
- *Other*: Cancer of the esophagus, stomach, colon, and pancreas; pleural plaques, pleural thickening, and pleural effusion.

Under current regulations, asbestos waste generators (such as building owners) involved in a project requiring ACM removal must be identified and recorded. Liability is not eliminated by transferring the care, custody, or control of the ACM to a landfill owner. Original parties can be held legally accountable even if injury is sustained years after the removal project is completed. Thus, ACM burial in a landfill does not end the liability of the waste generators.

Asbestos is a general nomenclature given to a group of naturally occurring, hydrated silicate minerals that exhibit a fibrous morphology. Included in this group are the minerals chrysotile, crocidolite, anthophyllite, and some of the tremolite-actinolite and cummingtonite-grunerite series. All except chrysotile are known as amphibole. Although chrysotile is the least abundant form of asbestos, it is the most commercially important form due to its mechanical strength, thermal stability, and low thermal conductivity (5). General elemental composition for each asbestos type is listed at Appendix A.

The fibrous morphology of asbestos allows respirable asbestos particles to become lodged in the lung walls causing scarring that eventually leads to asbestosis or mesothelioma, both of which can be fatal. Due to the health hazards associated with airborne asbestos, new asbestos use has been restricted by the Asbestos Ban and Phase-out Act, and occupational exposures set by OSHA regulations. An "asbestos fiber" is defined by the National Asbestos Safety Council as a particle longer than five microns, with a length-to-diameter ratio of at least 3 to 1 (6).

Melting points for asbestos minerals range from 1193 °C for crocidolite to 1521 °C for chrysotile (7). Decomposition of asbestos forms occur in the range 530-915 °C to

Table 1. Asbestos decomposition products (5).

Asbestos Type	Temp / Pressure	Decomposition Products
Chrysotile	800 °C	Forsterite + Quartz
Crocidolite	530 °C @ 3 kbar	Hematite + Magnesioferrite + Actinolite + Quartz
Anthophyllite-Gedrite Series <ul style="list-style-type: none"> • Anthophyllite • Gedrite 	800 °C @ 5 kbar	Orthopyroxene + Quartz
Cummingtonite - Grunerite Series <ul style="list-style-type: none"> • Amosite • Montasite 	800 °C	Forsterite + Orthopyroxene + Quartz
Tremolite-Ferroactinolite Series <ul style="list-style-type: none"> • Tremolite • Actinolite 	915 °C @ 15.5 kbar	Enstatite + Diopside + Quartz
Hornblende <ul style="list-style-type: none"> • Hornblende • Pargasite • Ferrohastingsite 	840 °C @ 250 bar	Diopside + Forsterite + Spinel

form the products as listed in the Table 1 plus water of hydration (5). Previous asbestos vitrification research at Georgia Tech indicated that the dominate decomposition product, forsterite, is an orthosilicate material that is usually very leach resistant (8). A description of these products of decomposition is found at Appendix A. Since the elemental composition of each of the asbestos forms can vary slightly, the products of decomposition also vary somewhat.

Previous Work (9,10,11)

The concept of disposing of ACM by thermal transformation is based on the fact that asbestos fibers melt and change in molecular structure at elevated temperatures. When asbestos is heated to 800-900 °C, it transforms to a flaky material called forsterite. Heating to temperatures above 1,000 °C melts the material into an amorphous, chemically inert material. These changes are irreversible; on cooling, the material solidifies, but the asbestos fiber structure is not restored. The residue material is not considered to be asbestos, and is classified as nonhazardous. The USEPA has acknowledged that this thermal vitrification process is sufficient to render asbestos and ACM harmless.

The results from the CPAR Phase 1 program successfully demonstrated that plasma arc technology is a feasible process for the destruction of the asbestos material:

1. Plasma arc technology was demonstrated to be an efficient and effective method of destroying and vitrifying pure chrysotile asbestos in an environmentally safe manner.
2. Only a few scattered fibers were found in the trace amounts of asbestos found in the solid residue and gaseous effluent during the analysis. The levels are considered negligible, and are below the exposure standards and guidelines for asbestos exposure (i.e., less than 1 percent by volume in the solid vitrified materials and a maximum airborne concentration of 0.2 fibers per cubic centimeter in the workplace).
3. There is high probability for safely destroying asbestos, ACM, and other contaminated building materials with plasma arc technology.
4. The ability to provide a mobile Plasma Asbestos Pyrolysis System (PAPS) that can effectively process over 7 tons per day is considered commercially competitive in many regions of the nation where the landfill costs are above average. As the disposal costs increase for landfills, the use of new technologies such as plasma arc vitrification are expected to become increasingly competitive.

Based on the capability of high temperatures to destroy ACM, several competing organizations have been developing commercial vitrification processes using conventional heating technologies such as fossil fuels and electric furnaces. A thermal destruction process for ACM would be attractive to waste generators and landfill owners because it would eliminate their continuing liability, as discussed earlier. However, because temperatures greater than 1,000 °C are difficult to achieve and maintain in conventional furnaces, additional measures must be taken to assure that the destruction process is complete. These additional steps significantly impact the technical and economic viability of ACM vitrification processes based on conventional technologies. Existing conventional ACM vitrification processes generally require one or more of the following measures to ensure ACM destruction:

- long furnace residence times at elevated temperatures (up to 12 hours)
- addition of cullet (crushed waste glass) to promote the melting of the ACM, improve glassification of the residue, and more effectively immobilize any residual asbestos fibers
- presorting and separate treatment of ferrous and nonferrous ACM and asbestos-contaminated material
- shredding the ACM before feeding it into the furnace.

Even with the above measures, the residue from conventional thermal destruction processes is often not completely melted and vitrified. For example, the vitrified

material may contain unmelted metal debris from the original raw material. This could reduce the salability of the residue material (for road or concrete aggregate, etc.), which could in turn result in a requirement to landfill the residue.

Plasma Arc Technology (12,13,14,15)

General

A plasma is a gas that has been ionized by intense heat, such as that created by the electric arc of a plasma torch. Unlike nonionized gases, plasma can respond to electrical and magnetic fields; the resistance of plasma to an electrical field converts the electricity into heat energy. This technology was developed more than 30 years ago in the U.S. space program to simulate re-entry temperatures on heat shields. Only recently has the technology begun to emerge as a commercial tool in several industries, including steel making, precious-metal recovery, and waste disposal.

The heart of this technology is the plasma arc torch—essentially a steel cylinder several inches in diameter and several feet in length; the specific dimensions are related to the torch power levels. Plasma torches normally operate in the 100 kilowatt to 10 megawatt power range, and can routinely create controlled furnace temperatures that range from 4,000 to more than 7,000 °C. Thus, plasma torches can operate at much higher temperatures and at much greater efficiencies than fossil fuel burners. Furthermore, plasma torches require only about 10 percent of the air necessary for fossil fuel burners. Therefore, effluent gases are greatly reduced compared to fossil fuel burners, and furnace systems can be built much more compactly than conventional furnaces, at correspondingly lower capital costs. Additional information on plasma arc technology is given in Appendix B.

Advantages of Plasma Arc Heating

The advantages that accrue from the use of plasma torches include:

- *High Temperatures:* The plasma torch can create temperatures not possible with fossil fuel burners. A plasma arc torch can routinely achieve controlled temperatures greater than 7,000 °C. This extreme heat is produced instantly and can be readily automated. Controlled high temperatures increase potential feed material throughput rates, and reduce costs.
- *Controlled Atmosphere:* Because the plasma arc torch is compatible with almost any type of gas (e.g., reducing, oxidizing, neutral, inert, etc.), the furnace atmosphere can be controlled to meet unique requirements.

- *Massless Heat:* Plasma arc torches use less than 10 percent of the air needed by fossil fuel heaters. Releasing heat energy with almost no mass is a simpler process than conventional heating, and offers greater control and efficiency. It also reduces offgas handling and other capital costs.
- *High Thermal Efficiency:* The efficiency of plasma arc torches consistently reaches between 85 percent and 93 percent. Therefore, the faster and more complete reaction kinetics of plasma energy sharply reduces required processing time and operating costs.

Plasma Torch Types

There are two basic types of plasma arc torches. On the *Transferred Arc Torch*, the positive attachment point is at the rear electrode and the negative attachment point is the workplace of the melt. For example, if metal scrap is being melted, the negative attachment point is the metallic scrap. On *Non-transferred Arc Torches*, both attachment points are within the torch itself and only the generated plasma flame egresses from the torch.

Plasma Heating System Components

The plasma arc torch is only one component of the plasma heating system. The other principal components are: (1) a *power supply*, which can be either alternating current or direct current; (2) a *control panel* to control the initiation and sustainment of the plasma arc column; (3) a *closed-loop water system* to provide cooling to the electrodes and shroud; (4) a *gas system* to provide the small quantity of gas required to create the plasma; and (5) a *starting system* to start the torch.

Plasma Arc Technology Applications (14, 15, 16, 17)

Several plasma arc torch processes for the destruction of hazardous and toxic wastes have been developed and successfully tested. Research on a variety of waste materials has been conducted using plasma energy. The very high temperatures and energy densities, in conjunction with the ionized and reactive medium, have fully demonstrated the potential of plasma arc technology to eliminate many waste materials in an environmentally safe and cost-effective manner. Materials vitrified with plasma arc torches readily pass all standard leaching tests. Thus, if pure asbestos can be destroyed in an environmentally safe manner, then it is likely that

asbestos, ACM, and any other materials removed from a building can also be mixed, vitrified, and similarly destroyed in an environmentally safe manner.

Plasma technology was the topic at the 1st International Conference for the Stabilization and Valorisation of Ultimate Waste (Metatechnies 1994) held in Bordeaux, France in September 1994 (23), and the 2nd International Symposium on Environmental Technologies: Plasma Systems and Applications held in Atlanta, GA in October 1995 (20, 21). Plasma arc torch technology is currently being used or planned for a variety of industrial and experimental applications (Table 2).

Table 2. Industrial and experimental applications for plasma arc technology.

<ul style="list-style-type: none">• Titanium scrap melting• Coal gasification• Ferro-alloy production• Molten steel ladle heater• Aluminum recovery from dross• Volume reduction of equipment• Tundish heating for steel casting• Incinerator ash vitrification• Iron ore reduction• Waste pyrolysis (municipal, medical, asbestos, tires, hazardous/toxic, low-level radioactive)	<ul style="list-style-type: none">• Biomass energy conversion• Shale oil recovery• Platinum recovery• Zinc recovery• Chemical Synthesis• MgO refractory production• Powder metal production• Silicon metal production• Electric arc furnace dust vitrification• Glass melting
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3 Research Plan

General

This research program investigated the feasibility of the development of a mobile Plasma Asbestos Pyrolysis System (PAPS) for the processing and disposal of asbestos-containing materials (ACM). The research tasks addressed the issues necessary for providing basic design criteria for a prototype PAPS. The CPAR Phase 1 program established that the plasma arc technology was appropriate for pure asbestos material. The evaluation for ACM processing was performed under this CPAR Phase 2 program.

Research Tasks

The major research tasks for this phase involved the following action items:

1. The improvement of the operational functions of the Plasma Applications Research Facility (PARF) at Georgia Tech. This would consist of establishing plasma systems and furnaces that can be used in the experimental asbestos vitrification program.
2. The testing of ACM in a plasma arc reactor processing system.
3. The analysis of the processed ACM product and the offgas from the process.
4. The determination of the Federal, State, and local regulatory requirements necessary to conduct the experimental program.
5. The ACM will be provided by an industry partner and controlled by approved regulatory compliance.
6. The experimental process will evaluate the asbestos handling and safety procedures, the feeding and extraction processes, the plasma arc torch operation, the auxiliary equipment requirements, the offgas effluents, and the processed products.
7. An economic analysis will be conducted to evaluate the cost-effectiveness of a PAPS prototype.

8. A final report will detail the results of the experimental testing program and the development of the PAPS basic design criteria.
9. Technology transfer initiatives within the DOD will be fully supported by USACERL, Georgia Tech, and the industry partners.

Test Facilities

The primary experimental testing was conducted at the Georgia Tech Plasma Applications Research Facility (PARF) in Atlanta, GA (Figure 1). The PARF contains two plasma heating systems: a 100 kW and a 240 kW plasma heating system (PHS) both built by Plasma Energy Corporation (PEC). A insertion-plunger furnace with a semi-batch feeding system, was designed for the 100kw PHS and fabricated by Plasma Technology Corporation for use on this program (Figure 2). The GTRI staff modified the unit to accommodate easier extraction and removal of the processed product. The original design for the graphite crucible was also modified to insert thermocouples and allow a larger quantity of ACM to be fed into the furnace during each test (Figure 3).

Asbestos-Containing Material (ACM) Test Samples

This experimental program consisted of tests using various types of ACM, as follows: floor tile (two types), transite wall board (1 type), and roofing material (1 type). These samples represent the most difficult ACM materials to destroy due to the highly bonded character of the materials (floor tile and transite) or the high hydrocarbon content of the material (roofing). These samples were obtained by Winter Environmental Services, Inc. (WESI) from their asbestos abatement projects of commercial facilities being renovated or demolished.

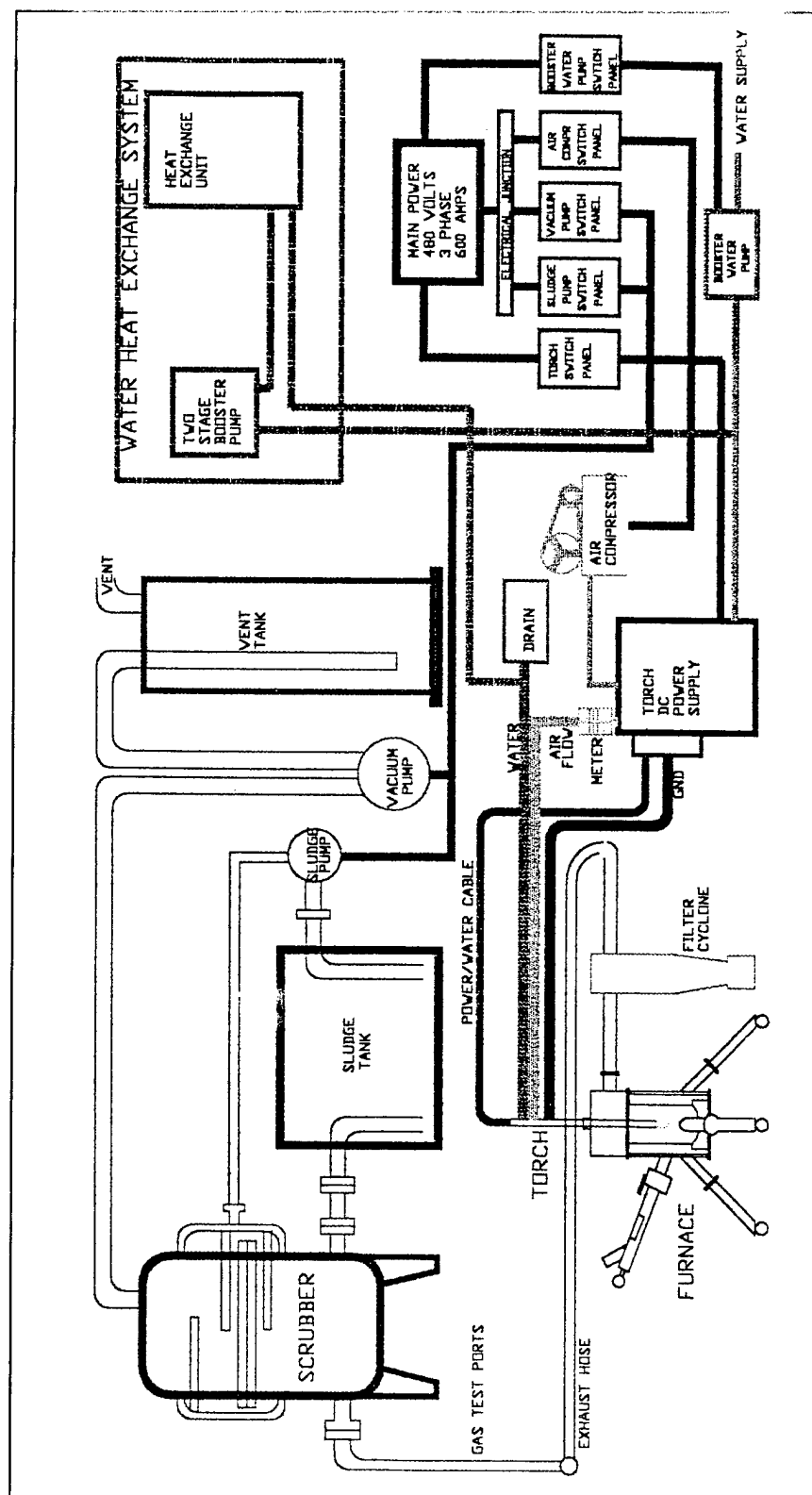


Figure 1. Overall system diagram, Plasma Applications Research Facility (PARF).

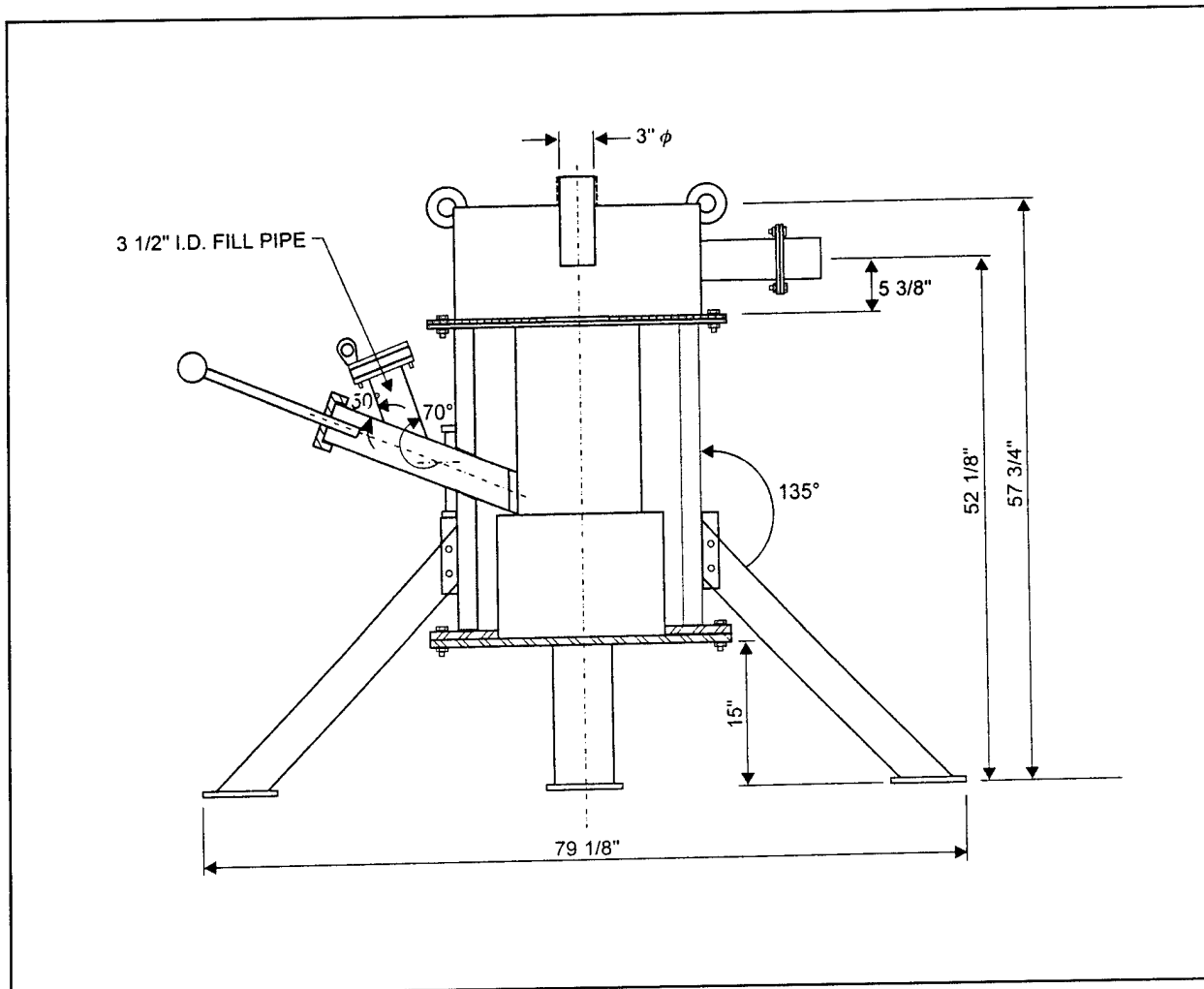


Figure 2. CPAR reactor/furnace sketch.

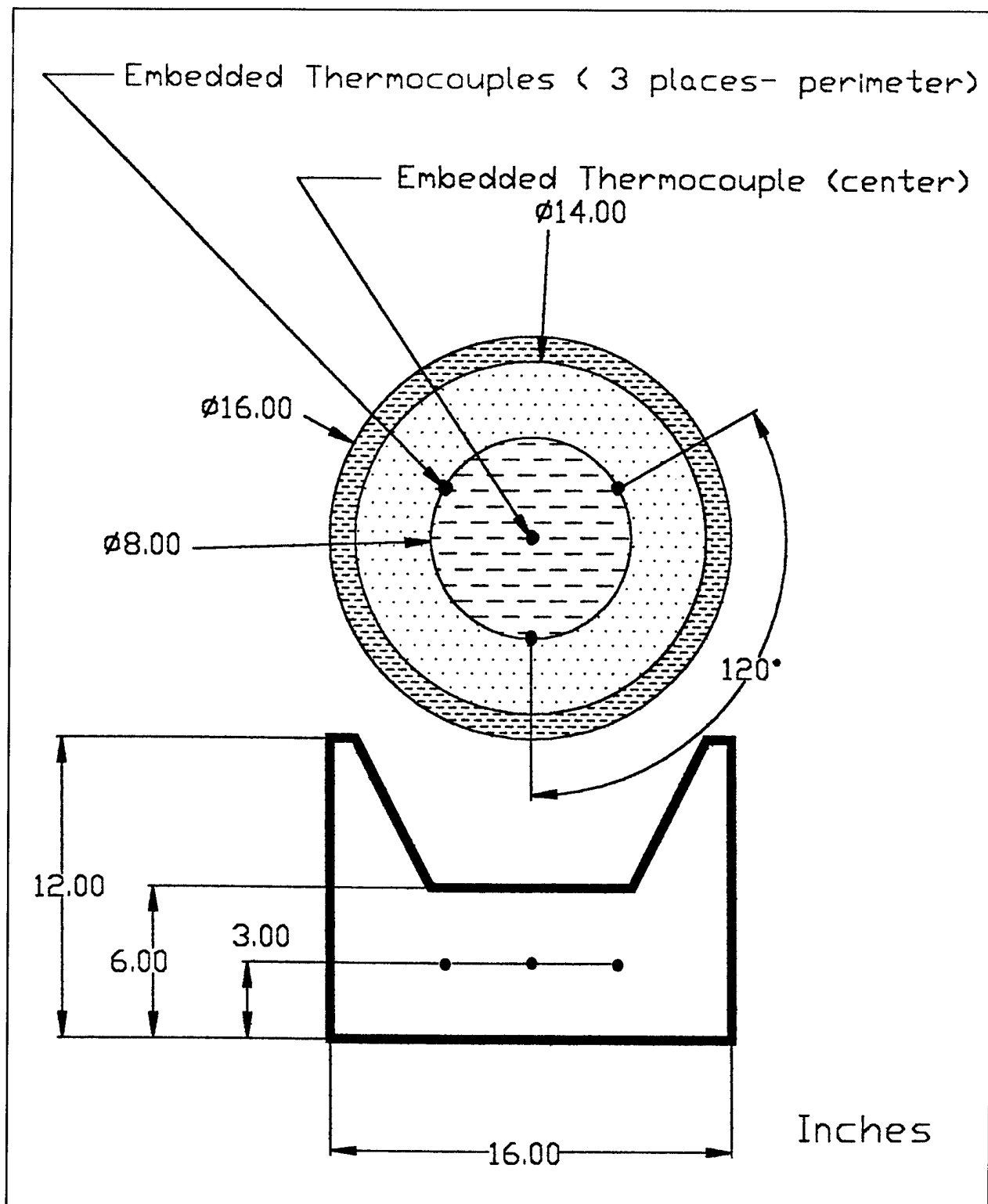


Figure 3. Reactor crucible with thermocouple locations.

4 Experimental Procedures

Sequence of Experimental Activities.

1. Develop a test plan and set up a schedule for conducting each experiment.
2. Establish plasma processing system specifications and design changes as appropriate.
3. Reconfigure and modify the plasma processing system as required.
4. Evaluate regulatory compliance procedures.
5. Obtain the sample material; document and analyze as required.
6. Package the sample material for processing (size, shape, container, etc).
7. Prepare the plasma processing equipment for the experiments.
 - a. Inspect and replace the plasma torch electrodes, as needed.
 - b. Inspect and replace the plasma torch o-rings, as needed.
 - c. Prepare the offgas system for the tests.
 - d. Prepare the plasma reactor/furnace for the tests.
8. Set up the thermal measurement instrumentation equipment.
9. Activate the plasma heating system (PHS), consistent with the operating procedures.
10. Preheat the reactor/furnace to the predetermined temperature.
11. Feed the test materials into the reactor/furnace as required by the test plan.
12. Following completion of the tests, implement the shutdown procedures for the PHS, consistent with operating procedures.
13. After the furnace cools to a safe thermal condition, open the furnace and remove the processed product for analysis.
14. Perform appropriate analyses on the processed product and gas samples as required by the test plan.
15. Clean and inspect the system in preparation for the next test.

Sample Preparation and Handling

Winter Environmental Services, Inc. prepared the ACM samples from materials removed from ongoing abatement projects. The ACM materials were identified, categorized, weighed, and then packed into canisters. The canisters are 3-in. diameter, thin gauge, carbon steel containers, sealed with duct tape. Each canister

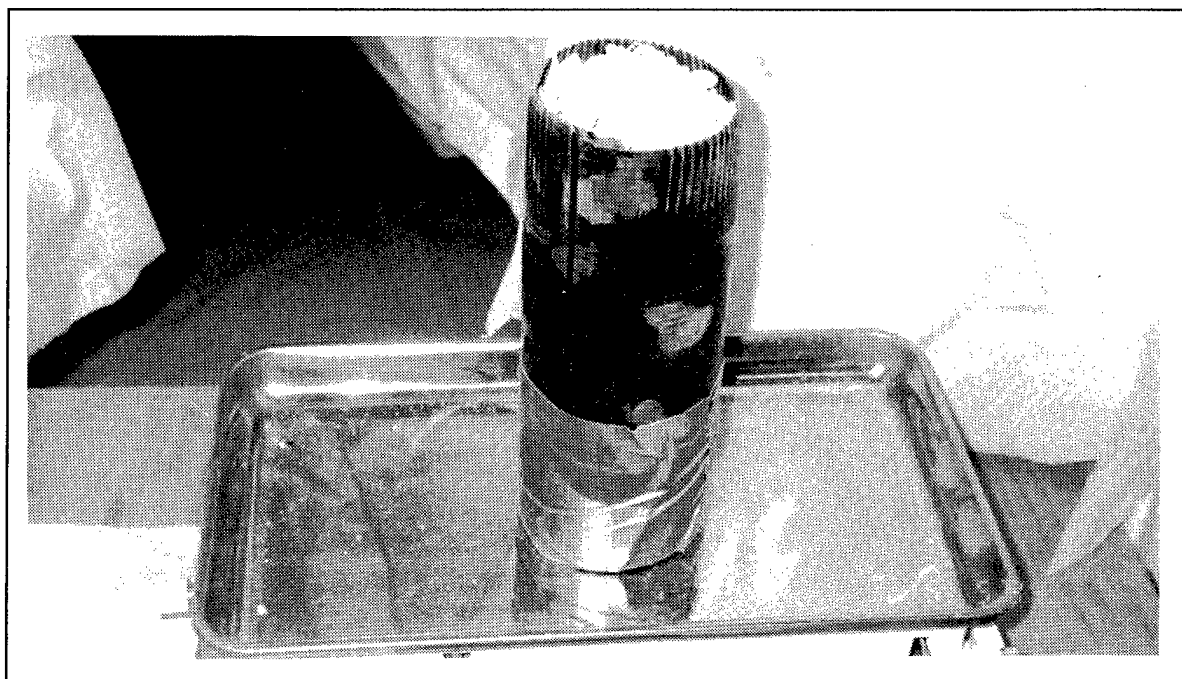


Figure 4. ACM Canister packing, Rocky Mountain Arsenal (RMA).

was 8.5 in. long (Figure 4). Total canister weight was determined at the conclusion of packing. The canisters were labeled for identification. Winter Environmental Services handled the sample injection into the reactor.

Thermocouple Locations

Four thermocouples were embedded in the graphite crucible (Figure 3). The location of the thermocouples was half the distance from the bottom of the crucible to the lower mounting plate. One thermocouple was located at the center of the crucible. The three perimeter thermocouples were located half the distance from center point to the edge of the crucible at 120 degree angles. Two additional thermocouples were located in the graphite wall of the reactor vessel, to be used as reference temperatures.

Start-Up Procedure

The first step in the start-up procedure was the preparation, calibration, and alignment of the experimental apparatus. These procedures included the preparation of cascade impactor collection substrates, calibration of the cascade impactor sampling pump, continuity checks of thermocouples, alignment and focusing of the pyrometer and video camera, calibration of the vacuum manometer,

and weighing/loading of the iron into the crucible for the molten metal bath, when required.

The plasma torch and furnace systems were next prepared for operation. Facility ventilation fans and the reactor exhaust fan were turned on. The packed bed scrubber system began operation. The plasma cooling water manifold was opened and the cooling water pump was activated; the water pressure and flow-rates were checked. The air compressor for the plasma gas was turned on. The power supply was checked for proper operation and the plasma torch was turned on. Torch operating data and water temperature data were recorded.

Preheat Procedure

The preheat phase duration was determined by the temperature of the central thermocouple which was embedded 3 in. below the bottom of the graphite crucible. When the thermocouple reached 1,000 °C, the canisters began to be fed into the furnace. The preheat phase was performed to allow the furnace to reach steady state conditions approximating an industrial furnace operation.

Plasma Torch Operations

The plasma torch was operational in the furnace at heights ranging from 9 to 15 in. above the bottom of the crucible. During processing, the height was adjusted to a level of 12 in. for normal operation.

Furnace System Pressure

During the experiments a negative pressure was applied to the furnace from the offgas scrubber unit. The negative pressure was maintained at an average of 3 to 4 in. of water.

Processing Time

The processing time allowed for each canister loaded into the furnace averaged around 5 minutes. A visual view of the melting process was provided by a video display during the testing. Observation of the thermal heating of the material was a guide to the feeding time interval.

5 Test Results

CPAR Experimental Data

Four experiments were conducted on the ACM provided by WESI from commercial sites. The samples consisted of floor tile (2 types), transite wall board (1 type), and roofing material (1 type). ACM samples were selected as representative of the more difficult material to destroy due to the highly bonded character of the (transite and flooring) material and the high carbon content of the (roofing) material. Table 3 lists specific information on each of the ACM samples used in the experiments.

Table 4 lists the test conditions and results of the four experiments. The results given are for the sample parameters, operational system data, exhaust analysis, and product analysis with the recovery fraction indicated. The experiments used a preheated procedure with and without a steel preloaded molten bath. A minimum temperature was set for 1000° C at the bottom center of the crucible as determined by thermocouple temperatures. The ACM canisters were fed into the crucible at approximately 5-minute intervals. A cascade impactor sample collection and Draeger tube measurements were made during the ACM canister feed period. The heating time between samples was determined by visual observation of the melt zone with the video camera.

Cascade Impactor.

The Andersen 1 ACFM Non-Viable Ambient Particle Sizing Sampler is a multi-stage, multi-orifice cascade impactor normally used in the environmental working areas to measure the size distribution and total concentration levels of all liquid and solid particulate matter.

Table 3. ACM sample information.

Experiment	Sample Type	No. of Canisters	ACM Weight (gms)
CPAR - 1	Floor tile	3	2,141
CPAR - 2	Transite panel	5	2,240
CPAR - 3	Roofing tile	6	3,120
CPAR - 4	Floor tile	6	2,716

Table 4. CPAR experimental test data.

	CPAR-1	CPAR-2	CPAR-3	CPAR-4
<i>Torch/system conditions</i>				
Steel melt (g)	2220	3330	None	None
Vacuum (in. of water)	3.5	3.0	4.0	3.5
<i>Torch height above crucible:</i>				
Preheat	15"	9"	15"	9"
Processing	12"-9"-12"	12"	12"-9"	12"-9"
Avg. Power (kW)	76.3	87.5	86.3	86.5
Average Torch pressure (PSI)	53.9	50.5	53.1	59.7
<i>Sample Parameters</i>				
Number of Canisters	3	5	6	6
Sample Type	floor tile	transite panel	roofing tile	floor tile
ACM weight (g)	2141	2240	3120	2716
Total weight (g)	2600	3744	3949	3562
<i>Operational data</i>				
Preheat time (min)	60	45	42	42
Processing time (min)	15	24	30	30
Post-processing time (min)	28	0	13	18
Total heating time (min)	103	69	85	90
Max. process temp. (deg C)	1804	1843	2260	1985
Min. Process temp. (deg C)	1539	1615	1510	1425
Final melt temp. (°C)	942	942	1326	948
Max. thermocouple (°C)	3450	1120	>5000	>5000
<i>Exhaust analysis</i>				
NOx	>5000ppm	>5000ppm	>5000ppm	>5000ppm
CO	1000ppm	300-500ppm	100ppm	>3000ppm*
HF	<1.5ppm	n/a	n/a	>7.5ppm
H ₂ S	<1.0ppm	n/a	<2.0ppm	<1.0ppm
<i>Product analysis</i>				
Product weight (g):				
Crucible	4198	5569	2322	2208
Wall	367	1431	715	206
Lid	0	150	148	44
Total	4565	7150	3185	2458
Recovery fraction	0.947	1.011	0.807	0.690
* Suspect data point.				

The Andersen Non-Viable Ambient Sampler was calibrated with unit density (1 g/cm^3) spherical particles so that all particles collected, regardless of their physical size, shape, or density are sized aerodynamically equivalent to the reference particles. In this manner, the aerodynamic dimensions obtained in the workplace can be used to determine:

1. Probable point of respiratory deposition
2. Particle behavior in the air
3. Type of control equipment needed to collect the particles
4. Compliance with existing Threshold Limit Values and OSHA Regulations.

A brief description of the operation of the sampling equipment follows:

1. Ambient gases enter the inlet cone and cascade through the succeeding orifice stages with successively higher orifice velocities from Stage 0 to Stage 7. Successively smaller particles are inertially impacted onto the collection plates. The submicrometer particles not collected by the last collection plate are caught in the backup filter, which is an integral part of the impactor immediately downstream from Stage 7. Stage 0 is an orifice stage only. Stage 8 is a collection stage only.
2. The clean gases are carried through the vacuum tube and through the pump and are then exhausted.
3. A constant air sample flow of 1 ACFM is provided by a continuous duty, carbon-vane vacuum pump. Flow rate through the impactor is controlled by an adjustable bleed valve on the pump, which requires periodic calibration.
4. After sampling is completed, the sample time is recorded and the tared collection plates and backup filter are removed for subsequent gravimetric and/or chemical determination.
5. Concentration levels are determined and the size distribution is plotted. At this point, the working environment can be assessed.

Data Analysis and Observations.

Analysis of the experimental data presented in Table 4 and in the attached appendices provides the basis for several observations and conclusions:

1. All asbestos-containing materials (ACM) which were subjected to temperatures above $1,000^\circ\text{C}$ were rendered nonhazardous by melting the asbestos fibers, pyrolyzing the organic material, and immobilizing the remaining contaminants, such as heavy metals, in the vitrified residue.

2. The molten metal bath used during processing in general reduces exhaust gas particle loading, and specifically suppresses the release of larger particles (>10 microns) into the exhaust gas stream. This observation is consistent with previous experiments (Appendix C).
3. The CPAR-2 cascade impactor data shows negative values due to poor experimental procedure (Appendix C). Note the reduction of particle loading from experiment CPAR-1 to CPAR-2. The cause of the reduced particle loading to the exhaust is uncertain since both the amount of steel in the crucible was increased, and the ACM input material was changed.
4. High hydrocarbon content ACM materials (roof tile of CPAR-3) evolved high concentrations of elemental carbon soot due to the overall reducing environment. This unexpected evolution of soot caused an overloading of the cascade impactor, invalidating the CPAR-3 particle sample gathered for that experiment.
5. Electron absorption elemental analysis conducted during scanning electron microscopy (SEM) analysis of the particulate matter collected in the cascade impactor revealed that the components of the particulate matter were similar, but the ratio of components varied (Appendix D). Elemental mapping (analysis not included) revealed that sulfur and chlorine were the major anions of the metal salts (white structures) seen in SEM photographs (Figure 5). The metal salts in CPAR-4 were almost exclusively metal-chloride crystals, which is validated by the high chlorine fraction seen in the electron adsorption data.
6. The NO_x concentration in the exhaust gas stream was greater than 5000 ppm during all experimental runs. The CO concentration varied between 100 and 1000 ppm. One observation recorded a CO concentration greater than 3000 ppm. (This CO data point is suspect.)
7. The average surface temperature of the product in the crucible during processing was greater than 1700°C, as measured by an optical pyrometer (Appendix E). The average surface temperatures by experiment were:

CPAR-1	1700°C
CPAR-2	1800°C
CPAR-3	1900°C
CPAR-4	1850°C.
8. The final product temperature, immediately after the plasma torch was turned off, was approximately 940°C. The final product temperature for CPAR-3 was 1320°C. The postulated reason for the difference was due to quartz roofing gravel present in CPAR-3 that increased silicon content of the product, and consequently the heat capacity of the product (Appendix F).

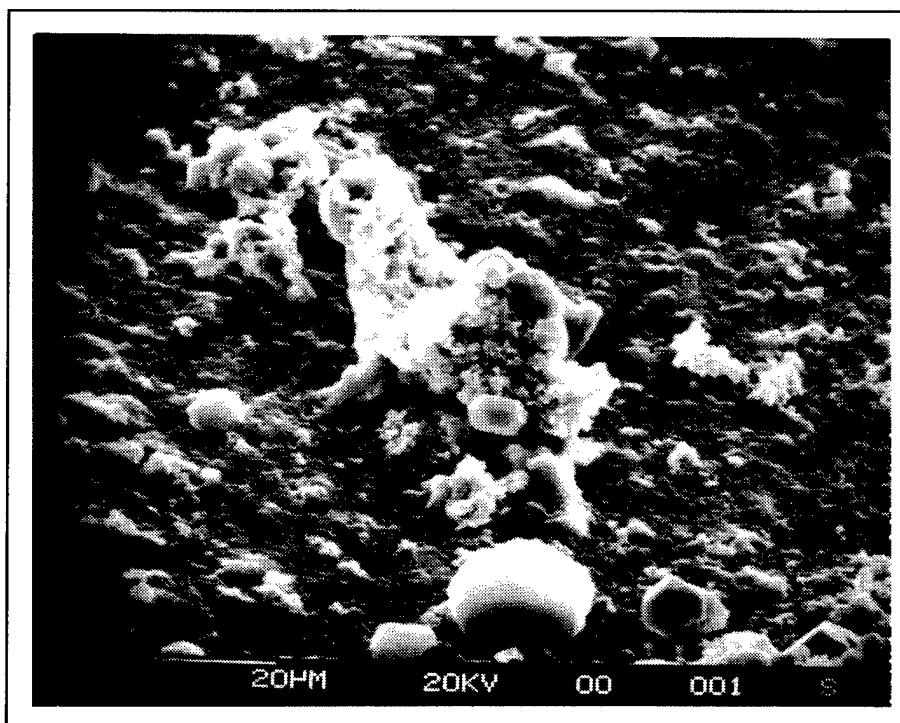


Figure 5. Crystals collected in cascade impactor.

9. The plasma gas interferes with the optical pyrometer readings as noted in the difference in the thermocouple data and pyrometer data (Appendix G). As can be seen from the data shown in Appendix G, the thermocouple and pyrometer data for CPAR-2 at torch shutdown are very close. The Type C thermocouples used in these experiments are considered valid only to 2,350 °C. Therefore, readings above this temperature should not be used as valid data points.
10. Thermocouple data show that CPAR-1 and CPAR-4 experienced cool spots in the reactor (Appendix H). CPAR-1 was run using an older electrode, which resulted in an off center plasma aimed to one side of the crucible. The torch was also off center on CPAR-4, causing a cool spot in the reactor. The reactor however was still able to reach processing temperatures. Subsequent observation of the crucible revealed what appeared to be unprocessed ACM. SEM analysis specifically investigated these "unprocessed" ACM particles, which revealed that the particles had in fact decomposed (Appendix I).
11. Appendix J includes the detailed experimental data comparing torch power levels and plasma gas pressures reported in Table 4. No correlation was indicated between torch power and product processing temperature.

Rocky Mountain Arsenal Experimental Data

In 1993-94, a series of ACM destruction and vitrification experiments were conducted on contaminated ACM from Rocky Mountain Arsenal (RMA) (18). Selected data contained in the RMA experiments are directly pertinent to the data requirements in this CPAR experimental program. Therefore, applicable data on the RMA experiments are provided in this report to augment the CPAR experimental data for the following reasons:

1. The RMA experiments involved several types of asbestos-containing materials (ACM) different from those used in the CPAR tests, permitting a more comprehensive list of ACM types to be examined.
2. The experimental setups in both studies were similar, permitting direct comparisons of data.
3. The RMA experiments formed the basis for the preliminary design of a stationary 1 ton per hour prototype plasma ACM vitrification system. This size is consistent with a PAPS prototype unit, and provided useful background information for the development of a mobile PAPS.

Eight vitrification experiments were conducted with ACM from Rocky Mountain Arsenal asbestos abatement projects. The ACM description provided by Rocky Mountain Arsenal showed three basic ACM types: loose tank/pipeline insulation, bonded transite and plasters, and sealing materials. Table 5 lists the general canister composition for each experiment; Appendix K provides detailed individual canister data. The first four experiments (TS-1 through TS-4) were tests to set operational parameters and establish the methodologies for sampling efforts. The final four experiments (FT-1 through FT-4) were the primary data collection effort with detailed gas analysis, provided by Geraghty & Miller, Inc., supplementing the analysis previously established in the preliminary tests.

The operational parameters were controlled to conduct the experiments such that the ACM was completely vitrified, while minimizing asbestos entrainment in the offgas. To achieve this end, the torch height above the ACM and torch power were maximized during processing, while carrier gas pressure/flow and system vacuum were minimized. Additionally, several tests were made with a molten metal bath in the crucible prior to injection of the RMA asbestos samples.

The 15 ACM samples from Rocky Mountain Arsenal were grouped into eight experiments and volumetrically packed into a minimum number of 3-in. diameter and 8-in. long canisters and sealed with duct tape (Figure 4).

RMA Experimental Test Data

Table 6 lists operational data from the RMA experiments.

Several observations were made governing the physical operation of the plasma vitrification unit. Splashing of the melted material in the crucible became evident due to a combination of a torch height that was too low and a plasma gas pressure that was too high. This resulted in unvitrified material being blown away from the plasma torch. In addition, molten material hardened in the valve/plunger assembly, making operation of these pieces difficult. The reduction of the carrier gas pressure appeared not only to reduce splashing, but also was somewhat effective in reducing the particle loading into the exhaust stream. The reduction of the system vacuum from 0.02 atmospheres to less than 0.01 atmospheres was also effective in the reduction of the particle loading to the exhaust gas stream. The use of a molten metal bath appeared to be useful in attenuating the formation of larger particles (> 10 microns diameter) in the exhaust stream. The molten bath did not appear to have an advantageous effect on the ability to more rapidly process ACM, reach a higher level of asbestos destruction, or provide better vitrified material physical characteristics.

The view port supporting the process video recording became severely pitted by molten metal particles that limited the quality of the process documentation in subsequent experiments. Deposition of particles onto the view port lens was also a problem during one experiment, causing a substantial degradation of video quality. The graphite release paint used on the interior crucible surfaces substantially decreased the erosion of the graphite crucible, while simultaneously allowing the vitrified product to be easily removed (Figure 6).

Table 5. ACM canister data.

Test Run	ACM Input				
	Number Canisters	Total Weight (g)	Percent ACM	VOCs (ppm)	Composition
TS-1	5	1693	61	1174	Tank covering
TS-2	10	3284	58	148	Pipeline/tank covering
TS-3	5	2160	68	29	Tank covering + sealing material
TS-4	3	2090	82	1173	Tank/pipeline/wall covering
FT-1	3	1327	72	20	Tank/pipeline/wall covering
FT-2	2	1376	83	1983	Tank covering + transite flooring
FT-3	4	2487	81	206	Wall mastic + tar + tank covering
FT-4	3	1272	70	?	Tank covering

Table 6. RMA operational data.

Test	Process Variable						
	Warm Up	Process	Post-Process	Max Temp (°C)	No. Canisters	Torch Height (in.)	Vacuum (Atm)
TS-1	25 min	25 min	14 min	>2200	5	12	0.021
TS-2	35 min	50 min	5 min	>2200	10	15	0.022
TS-3	45 min	25 min	21 min	>2200	5	15-12	0.021
TS-4	40 min	15 min	12 min	>2200	3	15-12-15	0.032
FT-1	53 min	15 min	10 min	1100	3	15	0.009
FT-2	32 min	10 min	11 min	>2200	2	15	0.006
FT-3	49 min	20 min	11 min	1600	4	15-12	0.006
FT-4	55 min	15 min	1 min	1500	3	15	0.006

Vitrified ACM Product

Visual Assessment of ACM Product

The visual assessment of the vitrified ACM product found an unevenly dispersed material that was once a molten mass. This vitrified mass contained predominantly dark material in the center of the crucible, with light colored material splashed on the crucible walls (Figure 6). Initial speculation suggested that the light colored material may have contained friable asbestos, which was disproved during SEM analysis. As the vitrified ACM was removed from the crucible, it was noted that the material crumbled easily. No tests were performed on the vitrified ACM to determine its use as a construction material.

Scanning Electron Microscope (SEM) Analysis

The SEM analysis of the vitrified ACM product revealed a similarity of physical appearance, with a variation in color (light/dark) due to the inclusion of air bubbles. SEM micrographs showed that the darker colored vitrified material (Figure 7) contained fewer air bubbles than the lighter colored vitrified material (Figure 8).

In over 20 hours of SEM analysis, only one suspect asbestos fiber group was noted (Figure 9). This fibrous inclusion in the vitrified material was found during the first asbestos experiment (TS-1) and was not noted in any subsequent experiment. Changes in operational procedures during subsequent experiments resulted in no

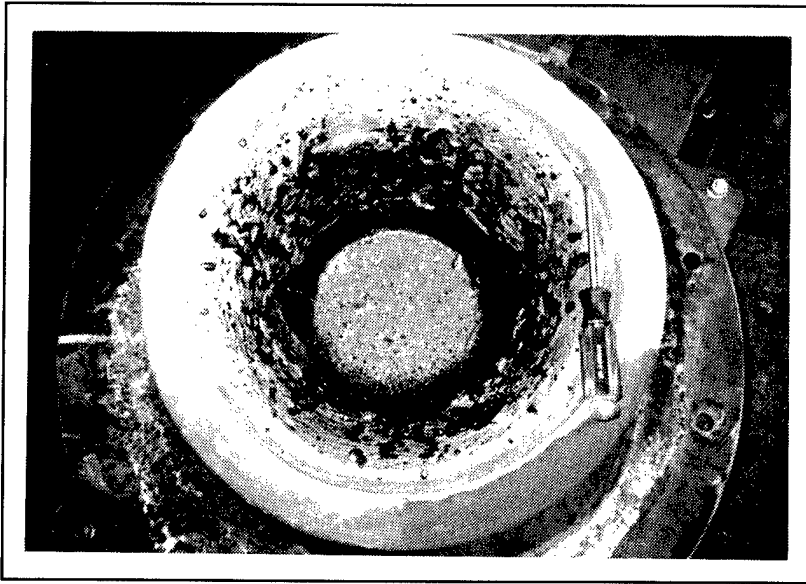


Figure 6. Crucible containing vitrified ACM from RMA.

further asbestos fibers found in the vitrified material. Electron absorption analysis of this particle indicated high levels of magnesium and silicon, which is indicative of chrysotile asbestos or its product of decomposition: forsterite (Appendix L).

Also evident in the SEM micrographs is the inclusion of iron crystals in the vitrified product, which are the direct result of the metal canisters and molten metal baths used in the conduct of this experiment (Figure 10). The high iron content areas made elemental analysis more difficult and less representative of the actual decomposition of the ACM. Electron absorption analysis of these two numbered spots on Figure 10 shows this iron interference (Appendix M).

Electron Absorption (EA) Analysis

The EA analysis of the vitrified product revealed general trends in its composition. Silicon was the most abundant component (ignoring iron) in the vitrified mass followed by calcium, aluminum, potassium, magnesium, and sodium. The presence of magnesium and part of the silicon were due to the asbestos decomposition; the other elements were associated with the binder materials and adhesives. The elemental composition of the vitrified product appeared to be heterogeneously dispersed in the melt since the proportions of elements changed within the same sample.



Figure 7. Dark vitrified materials.

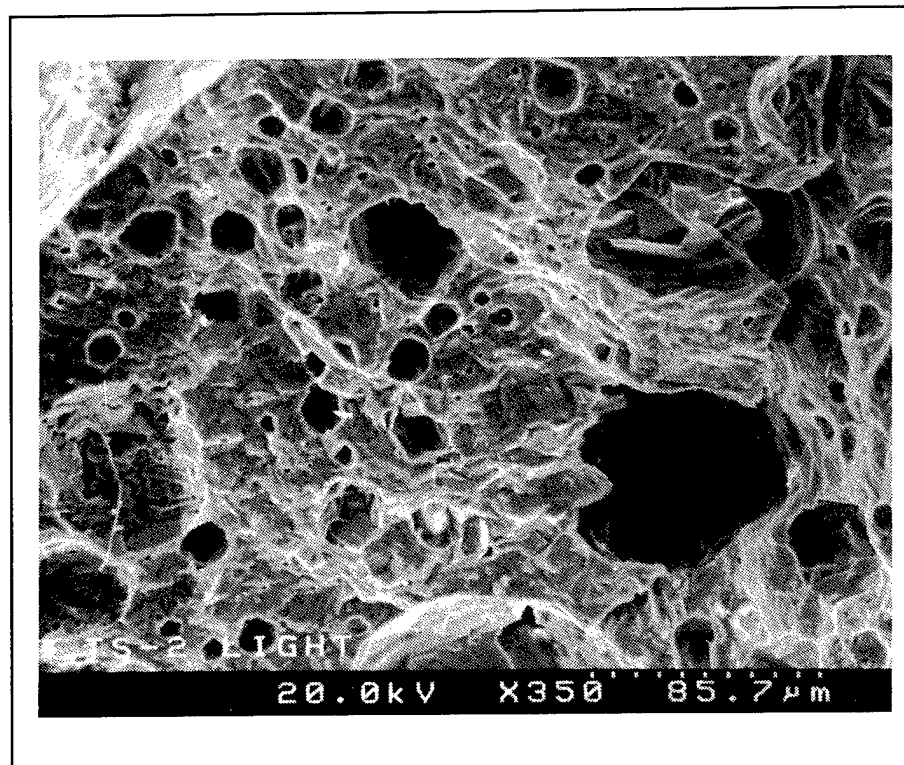


Figure 8. Light vitrified materials.

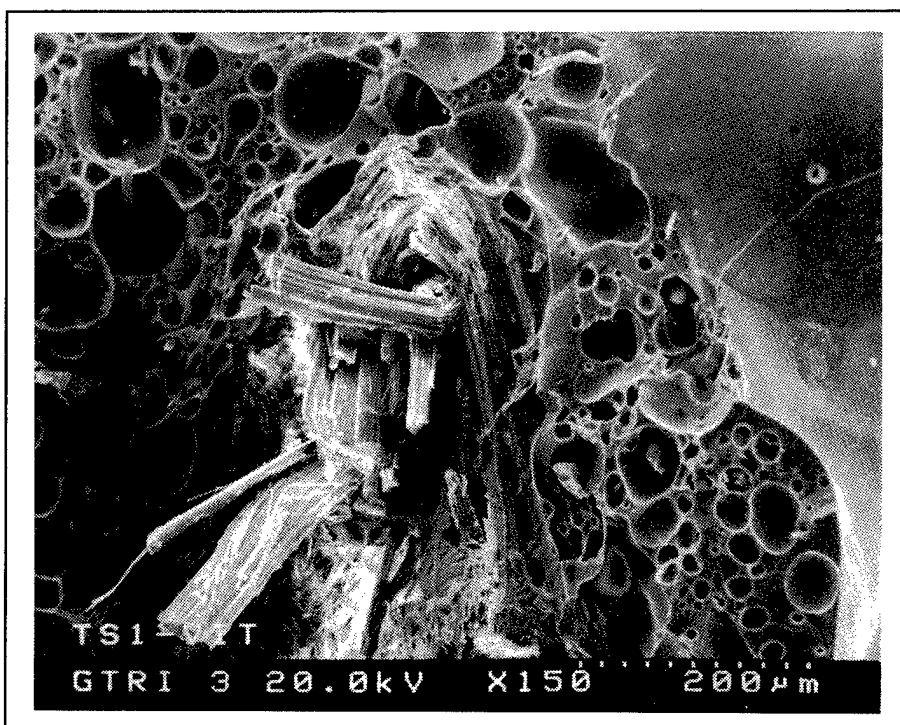


Figure 9. Suspect asbestos in vitrified materials.

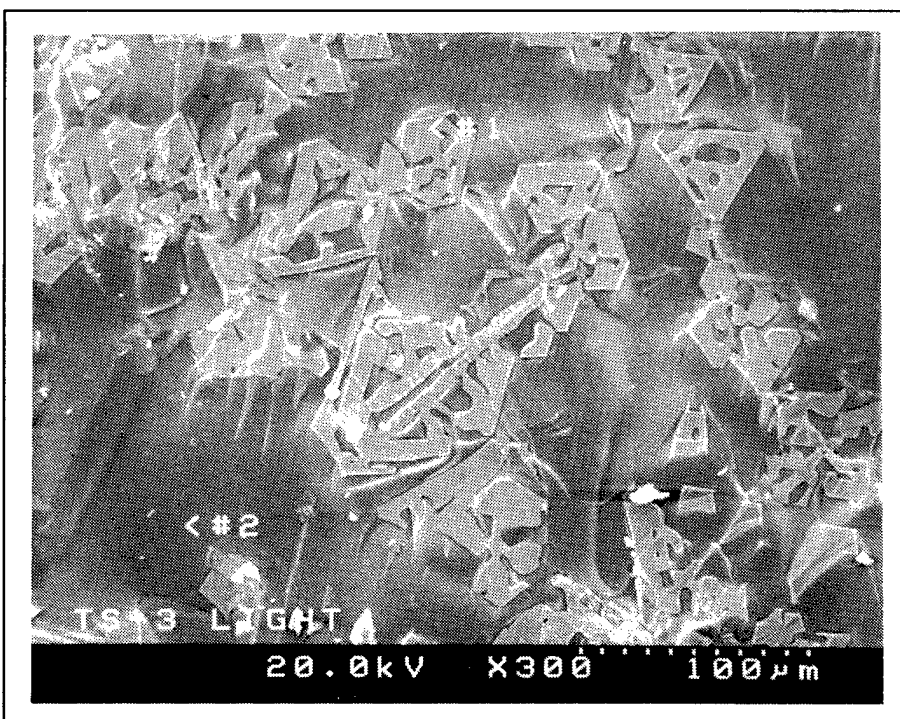


Figure 10. Iron crystals in vitrified materials.

Toxicity Characteristic Leaching Procedure (TCLP) Analysis

The TCLP analysis of the vitrified product revealed no significant leaching of any hazardous compound of interest to the USEPA. All compounds screened in the TCLP were below the detection limits for the test. The detection limits for all TCLP compounds are set at or below the USEPA hazard threshold.

Exhaust Particulate Matter

Gravimetric Analysis

According to the operating manual for the cascade impactor, 10 milligrams of particulate matter on any collection substrate represents an approximate upper limit because of re-entrainment problems. The manual further qualifies this by asserting that over-sampling can be visually determined. Instead of having well defined, discrete piles of particles, trails of particles can be seen leading from the sample deposits toward the periphery of the plate (19). Although each experiment had at least one section that exceeded the 10 mg limit, visual inspection of the collection substrates used in this experiment indicate only one experimental run where over-sampling was a problem. Inspection of Sample FT-3 noted the formation of stalagmites in sections 6, 7 and 8 that were toppled, but caught in the silicone spray in that same section. The liberal use of the silicon spray was noted during the SEM analysis to rise by capillary action between particles preventing re-entrainment of particles. It will be assumed that re-entrainment was not a significant problem during the conduct of these experiments. Particulate data for experiment TS-4 was lost due to a system failure, and are therefore not presented.

The bar chart shown in Figure 11 depicts the total mass of particles released into the exhaust gas stream divided by the mass of ACM input into the reactor during the experimental run. The results for the later FT experiments show fairly consistent mass loading from the vitrification process to the emission control system of 0.01 percent. Since ACM type changed for each FT experiment, this indicated that particle loading to a particle control device can be assessed based on ACM input, without regard for ACM type. In other words, an ACM input of 1 ton (2000 lb) can be expected to generate approximately 0.2 lb of particulate matter in the exhaust. The USEPA considers two types of exhaust particles; therefore both are reported: all particles in the exhaust stream called "total suspended particles (TSP)" and "particles less than 10 microns in diameter (PM-10).

The next analysis of the impactor data centers on the particle size distribution (PSD). An examination of the gravimetric analysis data indicates a bimodal distribution of particles, with one mode centered in the 0.4 micron range and the other mode larger than 10 microns, as can be seen in the representative PSD reported (Figure 12). The existence of a bimodal size distribution suggests two mechanisms of particle formation. It is believed that the larger sized particles were the result of the initial fragmentation of the ACM samples, and the smaller particles were the result of vaporization and nucleation of processed material. The use of a molten metal pool inhibited the initial fragmentation of the ACM sample, thereby reducing the formation of the larger particles (Figure 13). The tightly bound ACM materials (mastic, plasters, and sealing materials) also served to reduce the initial fragmentation of the ACM sample, thereby reducing the formation of larger particles (Figure 14).

The gravimetric data was plotted on Log-Normal Probability paper to define the geometric mean and standard deviation of the data. Table 7 lists the geometric mean particle diameter and geometric standard deviation. Since insufficient data was collected in the size range greater than 10 microns to characterize the mean size and standard deviation of that particle generation mode, a geometric mean and standard deviation analysis was conducted only on the smaller mode, which corresponds to particulate matter less than 10 microns in diameter (PM-10). Note that the data reported in Table 7 will be somewhat greater than actual values for the smaller mode since the tail of the large particle mode extends into the smaller particle mode.

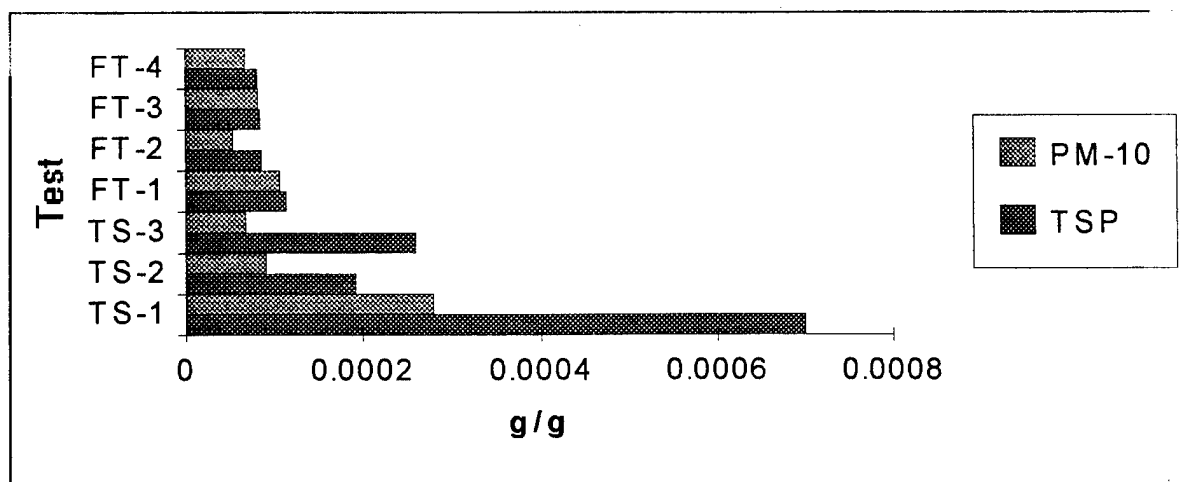


Figure 11. Total mass collected versus ACM input.

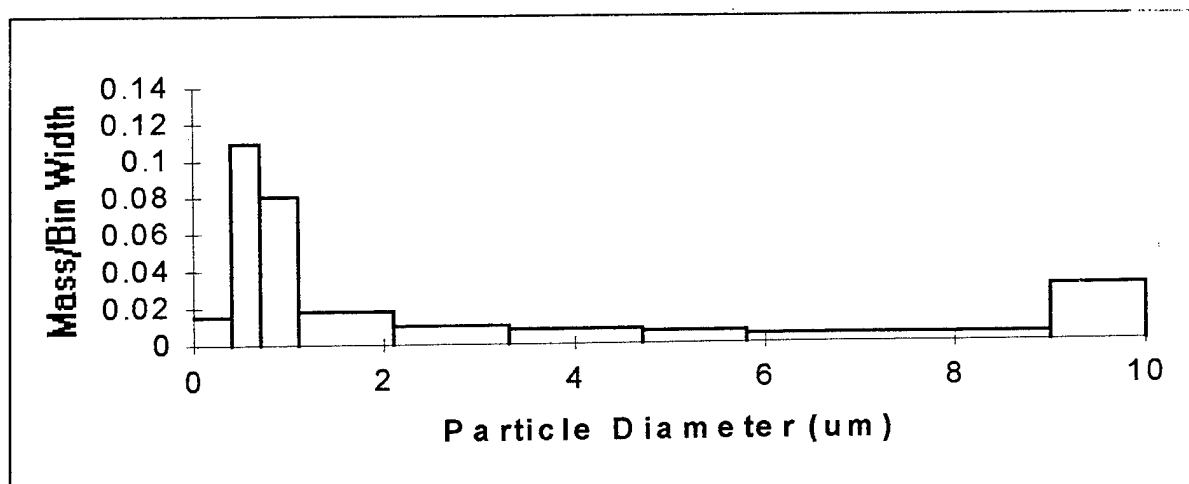


Figure 12. Experiment TS-1.

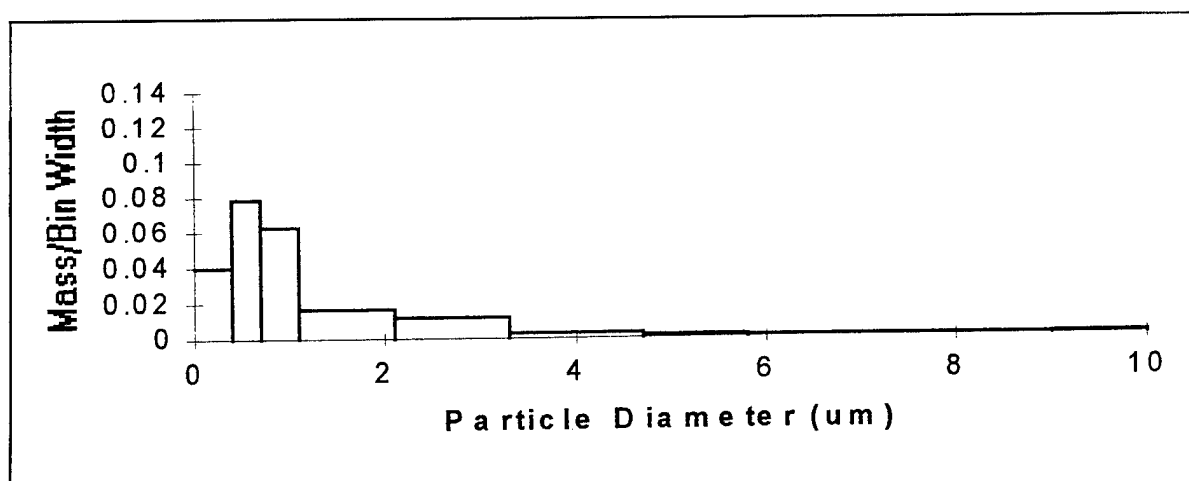


Figure 13. Experiment FT-1.

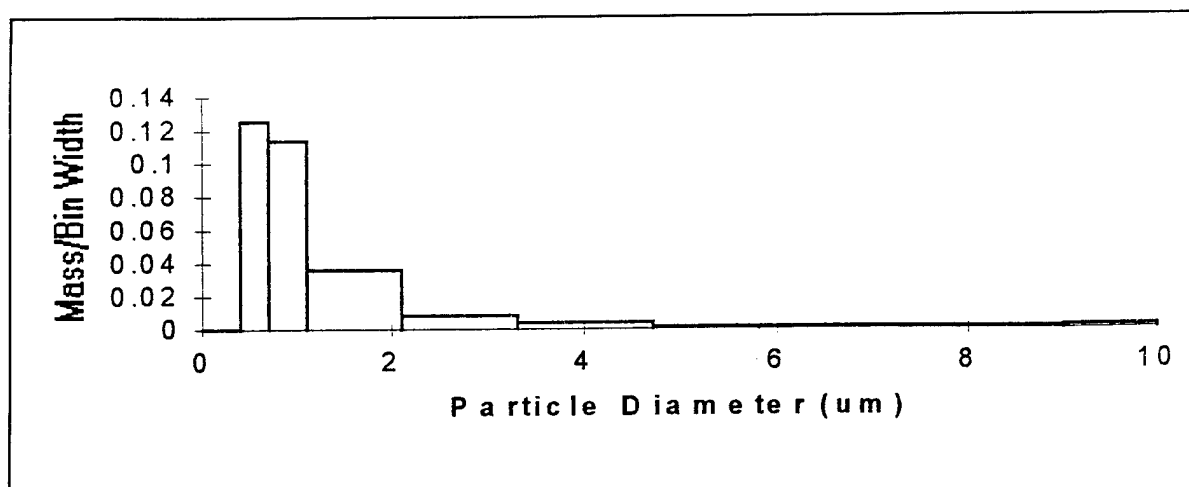


Figure 14. Experiment FT-3.

An analysis of the data in Table 7 shows a wide variation in means and standard deviations. This variation is believed to be due to a combination of operational parameters, ACM composition, and the use of a molten metal bath in two experiments. Tests FT-1 and FT-4 used a metal melt, which inhibited the initial fragmentation (large particle formation mode) of the ACM sample as shown by the mass collected in the preseparator (Table 8). The suppression of the large mode formation mechanism results in a lower standard deviation for the small mode particle distribution. Tests TS-3, FT-2, and FT-3 also showed mean values similar to those obtained using a molten metal bath. This skewing of the mean to smaller values is believed to be due to the rigid/adhesive binder used in the ACM, which retards the initial particle fragmentation.

Table 7. Geometric mean and standard deviation for RMA gravimetric analysis.

Test	Mean (μm)	Std Dev (μm)
TS-1	2.2	3.38
TS-2	2.4	5.71
TS-3	1.5	10.71
FT-1	1.0	2.08
FT-2	1.15	4.60
FT-3	0.78	8.97
FT-4	1.0	2.13

To assess the impact of the reactor/furnace and the sampling system additions to the mass collected on each substrate, a cascade impactor test was made during the warm-up phase of Experiment FT-2. Table 9 gives data for the blank and processing runs of this experiment that show a maximum of approximately 7percent of the collected mass from system additions, suggesting that the data collected during each sampling run has a precision less than the five significant figures collected in the raw data.

Exhaust Gas Analysis

The gas analysis performed by Geraghty & Miller focused on the determination of the exhaust flow rate and the exhaust concentrations of oxygen (O_2), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and total

Table 8. Large mode analysis data.

Experiment	Preseparator Mass	Melt Bath	ACM Sample Composition
TS-1	0.24418 g	—	Tank covering
TS-2	0.10335 g	—	Pipeline/tank covering
TS-3	0.26094 g	—	Tank covering + sealing material
FT-1	0.00674 g	Metal	Tank/pipeline/wall covering
FT-2	0.03696 g	—	Tank covering + transite flooring
FT-3	0.00355 g	—	Wall mastic + tar + tank covering
FT-4	0.00838 g	Metal	Tank covering

hydrocarbons (THC). The presence of high concentrations of ozone (O_3) interfered with the SO_2 analyzer, invalidating the collected SO_2 data. Table 10 summarizes the gas analysis data.

The values reported in the NO_x , O_2 , and CO_2 data collected during experiment FT-3 (3-I1, 3-I2, and 3-I4) and experiment FT-4 (4-I1, 4-I2, and 4-I3) are much lower than the data collected during all other sampling periods. This variation of data from expected values is easily explained by a leak in the sampling train that allowed a six volume dilution of the sampled gas stream. The compromise of the gas sampling train coincided with an impromptu experiment on the effects of various levels of vacuum on NO_x generation. Previous manipulation of the vacuum during experimental run TS-4 resulted in a similar loss of cascade impactor data due to a backwash of scrubber water. The generation of NO_x is a temperature dependent, free radical process where the diatomic oxygen molecule is broken into two oxygen free radicals. These extremely reactive oxygen free radicals are then able to attack the very stable diatomic nitrogen molecular bond, thereby creating nitrogen oxides. The concentration of oxygen free radicals increases as the temperature increases causing a proportional increase in nitrogen oxides.

Currently available NO_x control technology (selective catalytic reduction) can routinely control 80 percent of the NO_x generated in conventional combustion applications. Special emission control devices may not be necessary for plasma applications due to two features of plasma systems. First, the carrier gas can be changed from air to hydrogen, oxygen, argon or any other gas that does not contain a nitrogen/oxygen mixture, without loss of processing capability. Without the two primary components of nitrogen oxide being present in the plasma, no nitrogen oxide will be produced in the exhaust.

Table 9. FT-2 and blank sample analysis.

Section	FT-2 (g)	Blank (g)	% Error
1	0.00798	0.00018	2.26
2	0.00239	0.00003	1.26
3	0.00151	0.00009	5.96
4	0.00236	0.00011	4.66
5	0.00108	0.00007	6.48
6	0.00743	0.00009	1.21
7	0.013	0.00026	2.00
F	0.01309	0.00093	7.10
Final filter	0.01173	-0.00012	-1.02

Table 10. Gas analysis data.

Test No.	NO _x (ppm)	SO ₂ ⁽¹⁾	CO (ppm)	O ₂ (%)	CO ₂ (%)	THC (ppm)
1-11	5,000 ⁽²⁾	N/A	9,500	6.5	12.5	>10,000
1-12	3,000 ⁽²⁾	N/A	9,400	5.0	13.0	>10,000
1-13	4,300 ⁽²⁾	N/A	9,600	5.0	13.0	9,500
2-11	4,200 ⁽³⁾	N/A	9,700	2.0	8.75	No Data
2-12	4,300 ⁽³⁾	N/A	9,700	4.5	10.0	No Data
3-11	900	N/A	9,300	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
3-12	600	N/A	9,400	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
3-13	3,400	N/A	9,300	10	9	>10,000
3-14	800	N/A	9,300	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
4-11	500	N/A	9,300	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
4-12	600	N/A	9,300	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
4-13	500	N/A	9,300	— ⁽⁴⁾	— ⁽⁵⁾	>10,000
(1) Ozone interference - unable to calculate (2) NO _x level prior to injection - 7,000 ppm (3) NO _x level prior to injection - >10,000 ppm (4) O ₂ concentrations did not vary from ambient (5) CO ₂ concentrations did not vary from ambient ppm = parts per million						

A second mitigating feature of plasmas is the low carrier gas feed to the plasma. Although the exhaust gas stream contains high concentrations of NO_x and CO (approximately 10,000 ppm), the low 6.5 cfm carrier gas feed describes an annual NO_x emission of less than 1 ton per year. Emissions of criteria pollutants in quantities less than 30 tons per year are considered minor, and not subject to New Source Performance Standards and the most costly control technology (state regulations and ozone attainment status may alter this conclusion). Assuming a linear relationship between torch power and carrier gas feed, the NO_x emission for a 1.0 MW plasma torch would still be less than 10 tons per year.

6 Preliminary Design of a Mobile Plasma Asbestos Pyrolysis System

A preliminary design of a mobile Plasma Asbestos Pyrolysis System (PAPS) to destroy and vitrify asbestos-containing materials (ACM) has been developed based on the results of the two consecutive CPAR research programs and other related studies. This chapter outlines the basic design criteria and proposes a schematic layout of a mobile PAPS.

Asbestos-Containing Material (ACM).

The PAPS will be designed to vitrify ACM taken from large buildings and industrial facilities. The ACM will include pure asbestos wastes plus asbestos-contaminated materials normally removed from buildings by asbestos abatement contractors. The asbestos will be loaded into fiberboard drums, which are routinely used by asbestos abatement contractors. These drums can vary in size, up to 55 gal, depending on the final PAPS design. For the purposes of this study, 35-gal fiberboard drums, which will contain approximately 125 lb of ACM, are recommended. At a planned processing throughput of 1,250 lb per hour, a feed rate of 10 drums per hour (or one drum every 6 minutes) would be required.

Plasma Heating System.

Assuming an ACM Specific Energy Requirement (SER) of 0.40 kWh per lb (800 kWh per ton), a 500 kW Plasma Heating System (PHS) would have a capability to process 1,250 lb of ACM per hour. The plasma torch should have a transferred arc and be able to operate several feet inside a plasma reactor/furnace. Plasma Energy Corporation (PEC), one of the CPAR industry partners, produces such a PHS. The major components of their system are:

1. 500 kW Plasma Torch
2. Direct current power supply
3. Water-cooling console/pump station
4. Water-to-air heat exchanger

5. Air compressor
6. Water-gas manifold
7. Water-power junction box
8. Control panel
9. Power, water, and air linkages

Figure 15 shows a schematic diagram of a typical plasma heating system.

500 kW Reactor/Furnace With Drum Feed System

The reactor/furnace will be designed to accommodate a 500 kW plasma torch operating with a molten metal bath. The torch will maintain the bath temperature at approximately 1,600°C. Fiberboard drums will be loaded individually through a hydraulic feed system. The plasma torch will be articulated to permit drums to be fed into the reactor without obstruction, to vitrify any ACM that may not be completely processed in the molten metal bath, and to open the melted slag taphole if required. Figure 16 shows a proposed schematic diagram of a 500 kW reactor/furnace with drum feed system.

Gas Emission Control/Treatment System

The offgas generated in the vitrification process will be put under a negative pressure prior to entering the gas emission control and treatment system. This will ensure that all gases are directed through the entire gas emission control and treatment system prior to being exhausted to the atmosphere. Sludges, particulate matter and neutralization salts generated in the gas treatment systems would be collected and put through the vitrification process or otherwise treated. The PAPS gas emission and control system would generally consist of four components:

1. *Secondary combustion system.* The gases generated by the thermal process will likely contain combustible fuel gases. These will be totally burned in an off-the-shelf, standard secondary combustion chamber.
2. *Gas cooler / scrubber system.* The hot gases will be cooled and scrubbed in a gas cooler and scrubber system. Figure 17 shows a recommended design which has been successfully used for several years by PEC and Georgia Tech. The gases are cooled by passing through three sets of spray nozzles and a 2-ft bed of wet river bottom pebbles. Caustic soda is added to the water as required to neutralize acidic compounds in the offgas.

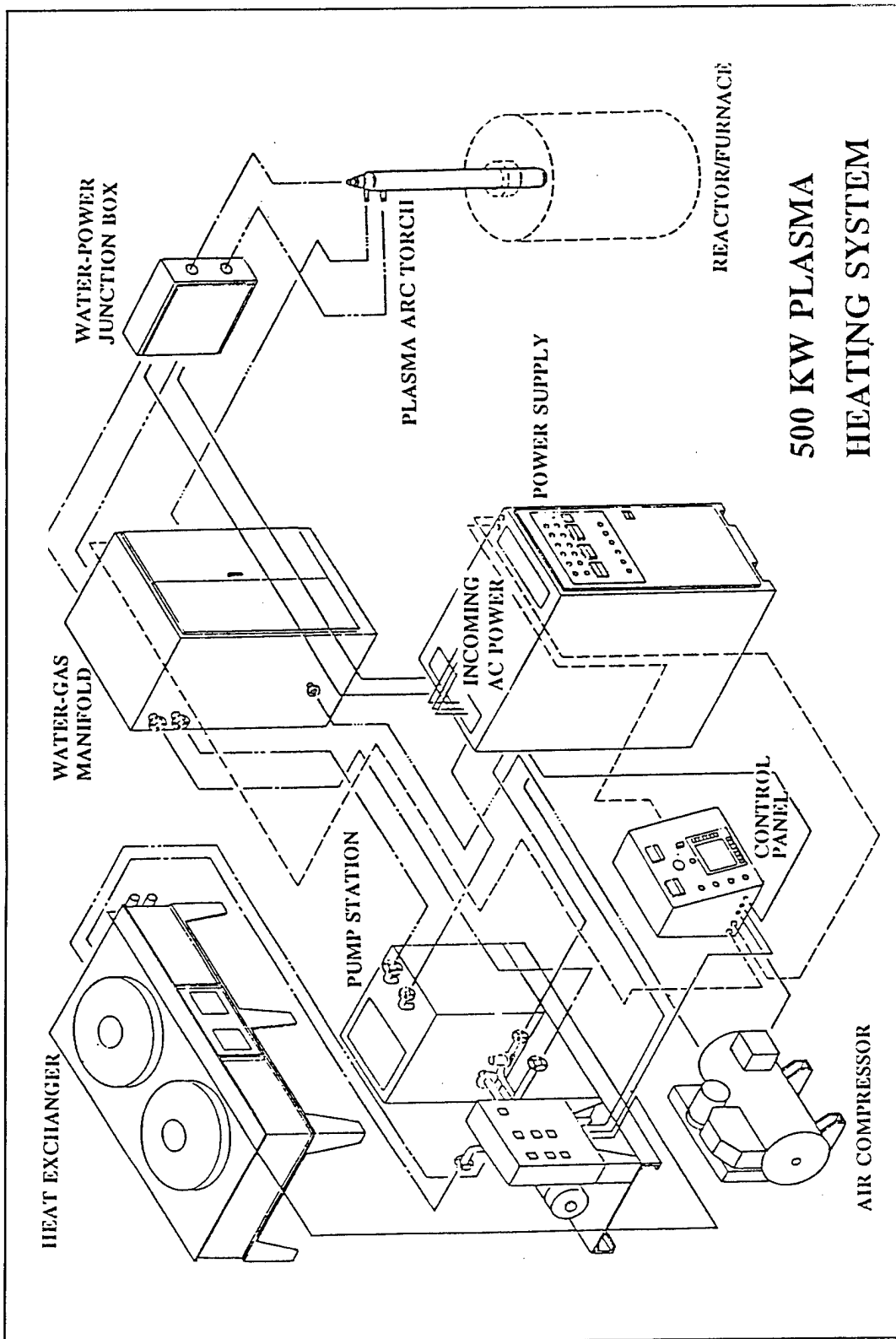


Figure 15. Typical plasma heating system.

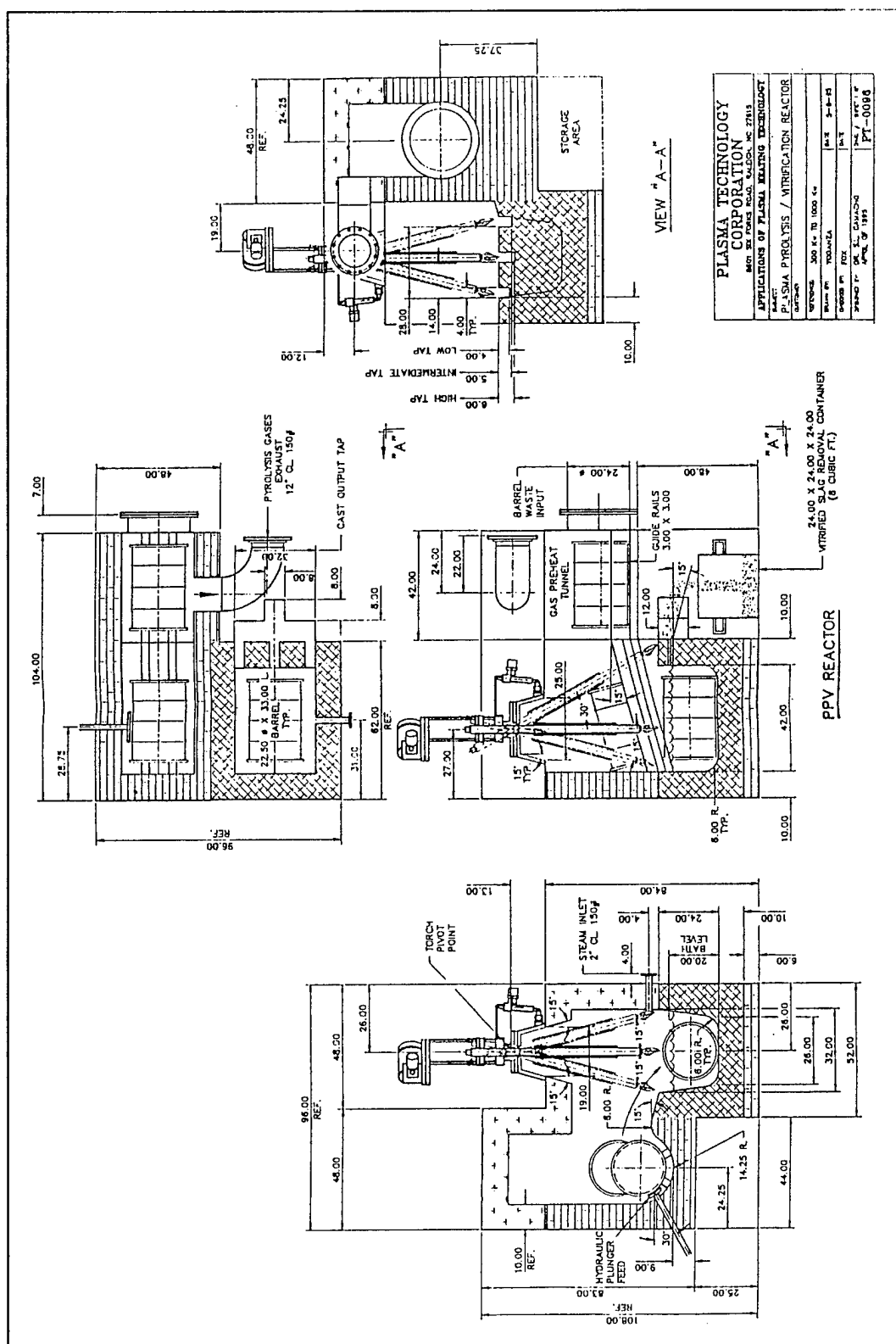


Figure 16. 500 kW Plasma reactor/furnace with drum feed system.

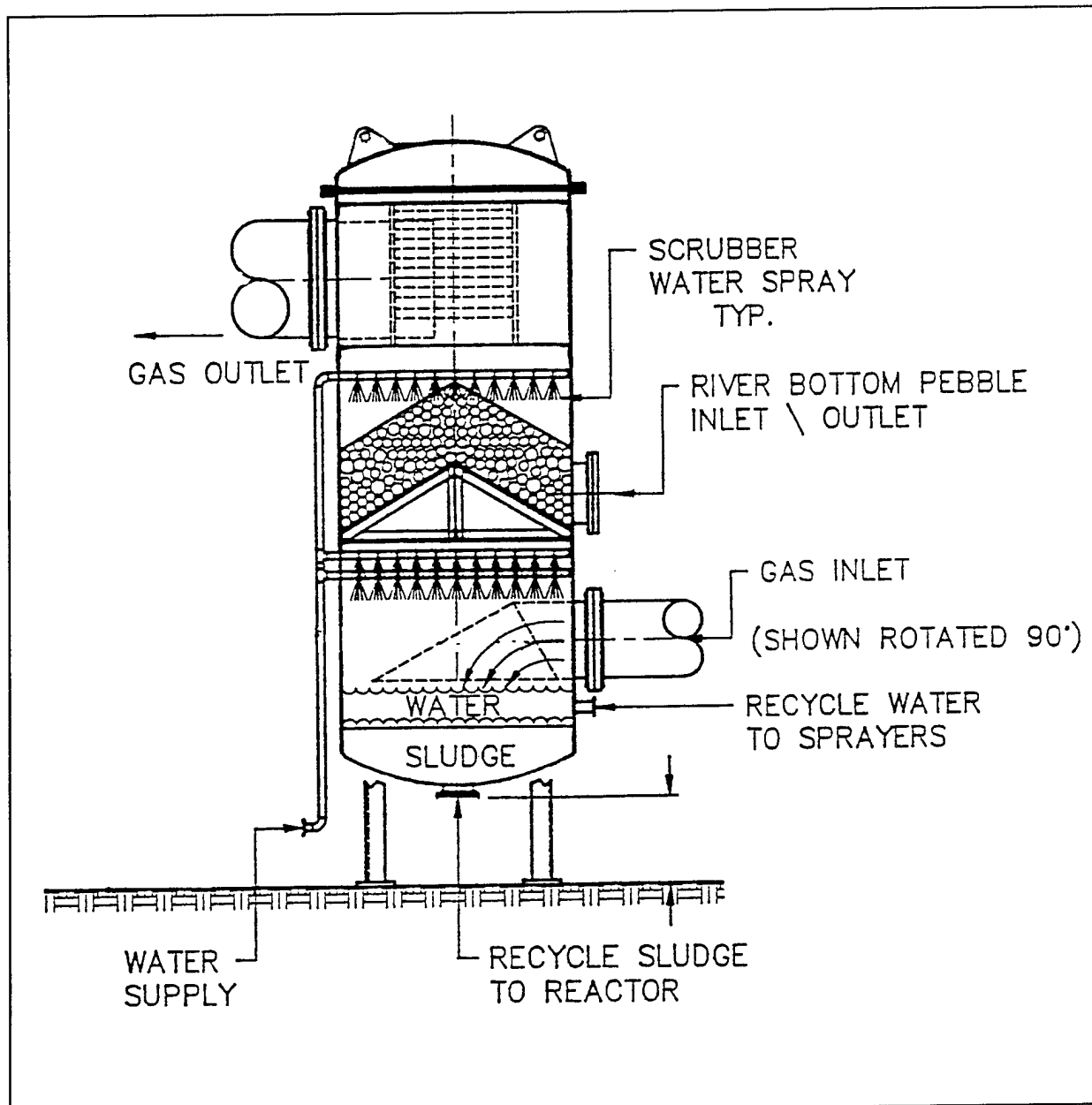


Figure 17. Gas cooler and scrubber system.

The assembled gas cooler/scrubber may stand too high to safely transport on a mobile system. Therefore, a design that would separate the system into two easily assembled halves should be considered. The schematic layout of the system recommended in this report assumes this configuration.

3. *Gas emission lime treatment system.* Allocation has been made in the PAPS design to treat offgas pollutants not remediated elsewhere in the gas treatment system. This condition could be caused, for example, by ACM contaminated with unique industrial chemicals, or simply by a scrubbing system overload.

In any case, special gas treatment requirements can usually be met with off-the-shelf gas treatment systems. For the purposes of this design, a simple dry-powdered lime gas treatment chamber has been included to treat residual acid gases not previously neutralized by the scrubbing system.

4. *HEPA filter.* Before release to the atmosphere, all exhaust gases will pass through a HEPA filter to ensure that no asbestos fibers or excessive particulates are released. HEPA filters are standard off-the-shelf items of equipment.

Vitrified Slag Handling Equipment

The molten residue material tapped from the reactor/furnace taphole would pour by gravity into a large mold for casting into glassy, rock-like ingots. When full, the molds would be replaced between taps by a forklift. The hardened residue has very high compressive strength (several thousand pounds per square inch) and could be readily sold as road gravel, concrete aggregate, etc.

Preliminary Design of a Plasma Asbestos Pyrolysis System (PAPS)

A recommended preliminary design and schematic layout of a mobile PAPS has been developed to indicate where the major items of equipment would be positioned. For the purposes of this study, standard 48-ft low-bed trailers were selected as the mobile platforms for the PAPS. Three 48-ft trailers were required to handle the major items of equipment for the PAPS (Table 11). Table 12 lists the equipment loading for each trailer. Figures 18, 19, and 20 show a preliminary design of each trailer load. The three trailers can accommodate the entire PAPS system except for the external electrical power requirement of 500 kW. For the main purpose of the construction industry, an asbestos rehabilitation project is normally co-located within an urban area with adequate supply of electric power at an industrially high voltage and power levels. In addition, construction companies generally have access to their own power generating equipment either directly or through lease arrangements for the specific periods they operate outside the range of an urban power supply network. Therefore, external power requirements were not included in the cost estimate for PAPS. However, if necessary, a fourth trailer could be added to the PAPS which could readily accommodate a 500 kW diesel generator unit.

PAPS Prototype Time Schedule

All equipment required for the design and development of a prototype PAPS is available off the shelf. No significant research and development effort would be necessary, except perhaps to adapt the equipment to a mobile configuration. Table 13 shows the time schedule for the design, development, and testing of a PAPS unit for implementation once a PAPS prototype unit is funded.

Table 11. Plasma asbestos pyrolysis system major equipment list.

1. Complete 500 kW Plasma Heating System:
a. Direct Current Power Supply
b. 500 kW Plasma Torch
c. Water-Cooling Console/Pump Station
d. Water-to-Air Heat Exchanger
e. Air Compressor
f. Water-Gas Manifold
g. Control Panel
h. Power, Water and Air Linkages
2. 500 kW Reactor/Furnace w/Drum Feed System
3. Gas Emission Control/Treatment System
a. Gas Cooler/Scrubber System
b. Gas Emission Lime Treatment System
c. HEPA Filter
d. Secondary Combustion System
4. Vitrified Slag Handling Equipment
5. 48-Foot Trailers (3 each)

Table 12. PAPS trailer loading plan; equipment breakdown by trailer load.

1. Trailer Number 1
a. 500 kW Plasma Heating System (PHS)
(1) 500 kW Plasma Torch
(2) Water Cooling Console/Pump Station
(3) Air Compressor
b. 500 kW Reactor/Furnace w/Drum Feed System
c. Vitrified Slag Handling Equipment
2. Trailer Number 2
a. 500 kW PHS
(1) DC Power Supply
(2) Heat Exchanger
(3) Water-Gas Manifold
(4) Power, Water and Air Linkages
b. Control Panel & Control Room
3. Trailer Number 3
a. Gas Cooler/Scrubber System
b. Gas Emission Lime Treatment System
c. HEPA Filter
d. Secondary Combustion System

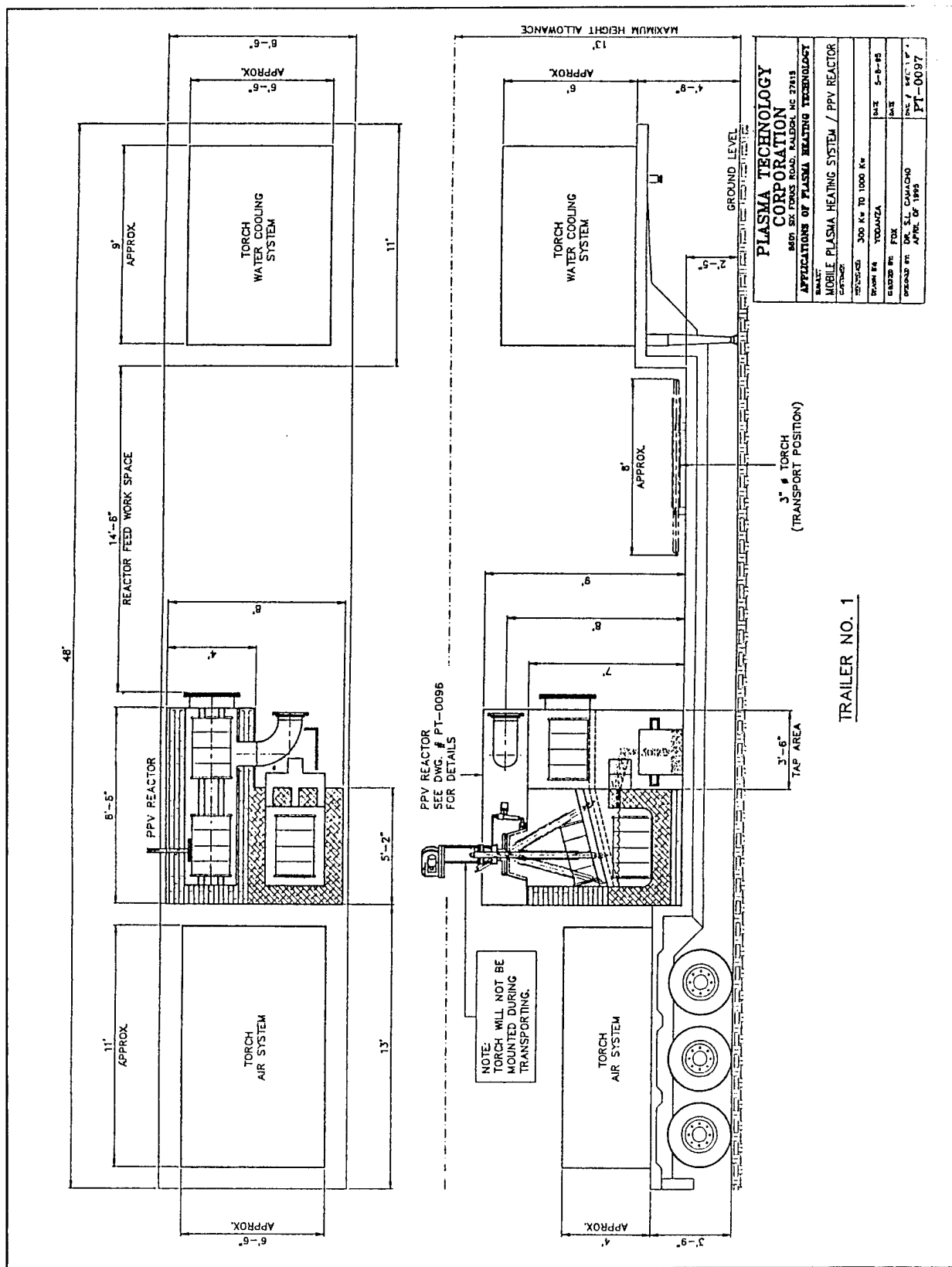


Figure 18. PAPS Trailer No. 1 equipment plan.

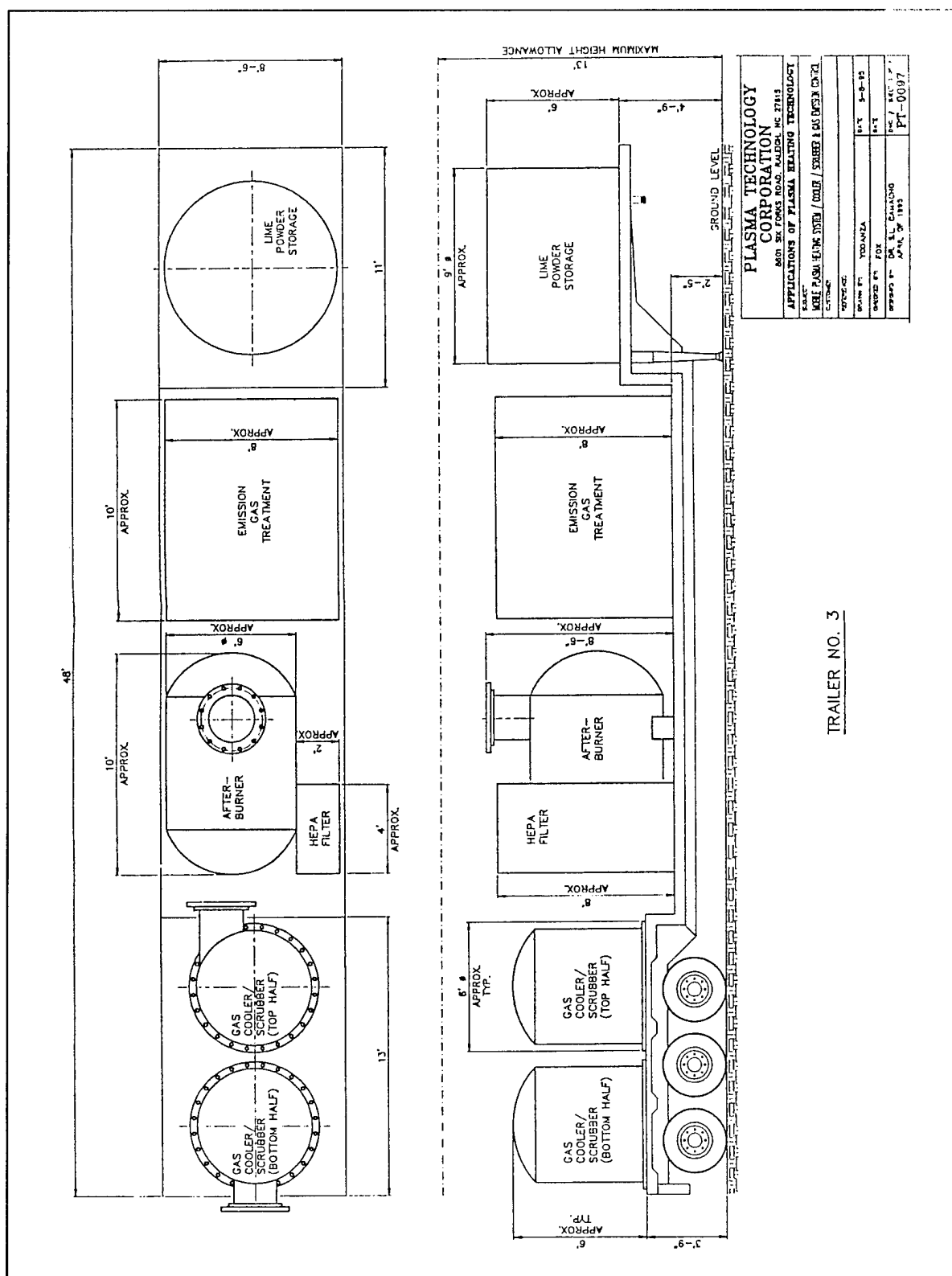


Figure 20. PAPS Trailer No. 3 equipment plan.

Table 13. Time schedule for design, development, and testing of a PAPS unit.

Activity	Time (Months)
PAPS Final Design	6
Equipment Procurement	9
System Integration	3
System Shakedown/Testing	4
Total	22 Months

7 Economic Analysis

Various assumptions could be taken at the outset of an economic analysis. The assumptions below are consistent with the experimental and technical protocol of this study, typical modes of operation for the plasma equipment, and a conservative estimate of various cost drivers for the application of plasma technology. For example, in their typical industrial applications, plasma furnaces are operated continuously (i.e., 24 hours a day) except for shutdown and maintenance. The reason for the typical continuous mode of operation is that the pre-heating and ramp-up periods are long, costly, and unproductive. In addition, the repetitive heating and cooling cycles deteriorate the furnace lining. Therefore, the typical mode of plasma arc heated equipment process calls for 24-hr operation and continuous feed rates. Construction industry practitioners, though capable of working long and extended hours, normally do not support around-the-clock work schedule except for emergency repair jobs and priority phases of the construction schedule. Rehabilitation of asbestos could hardly be considered one of the above items. Therefore, a 16 hour/day processing time was considered a practical compromise for the purpose of this economic analysis.

It was also envisioned that a critical mass of asbestos debris had to be collected on site prior to the application of the PAPS technology, thus allowing an economic rate for processing the feed material. Finally, the methodology outlined below could simply be used in a comparative sense or in the construction of a different case scenarios. Currently, the only other practiced method for ACM disposal is hauling to a Class-1 EPA-certified landfill with no treatment option. Landfills prices vary nationally depending on location and availability of landfill space. The price for disposal ranges from \$65 to \$160/ton in the Southeast and Midwest to a high of \$150 to \$300/ton in the East Coast or California. The two economic drivers that make the PEPS technology competitive are the escalating cost of landfilling process, with a 10 to 20 percent annual increase in the 1980s and the liability avoidance resulting from potential future litigation for any generator of tainted or contaminated ACM.

1. This economic analysis assumes:
 - a. Plasma Heating System (PHS): Treat asbestos-containing materials (ACM).
 - b. PHS Size: 500 kW, transferred arc torch

- c. Operations: 2 shifts per day
21.25 days per month
255 days per year
- d. Daily Processing Time: 16 hours
- e. Labor Costs: \$100,000 per year each shift
- f. Maintenance Costs: \$20/hr (torch @ \$10/hr; other at \$10/hr)
- g. Specific Energy Requirement (SER): 0.4 kWh per pound of ACM (800 kWh/ton) (Table 14)
- h. Power Cost: 5 cents per kilowatt hour
- I. Capital Investment Amortization: 10 years (n) @ 8% interest (i)
- j. Salvage Value of Capital Equipment in 10 years (V_{10}): \$95,000

2. Capital Investment Costs (V)

a. Plasma Heating System	\$500,000
b. Reactor/Furnace	85,000
c. Control Room	45,000
d. Gas Emission Control/Treatment	150,000
e. System Integration	40,000
f. Trailers (3)	60,000
g. Spare Parts	30,000
h. Installation/Start-Up	<u>40,000</u>
Total Capital Investment Cost (V)	\$ 950,000

3. Present Value of Salvage Equipment (V_s) is estimated as:

$$V_s = \frac{V_{10}}{(1+i)^n} = \frac{\$95,000}{(1+0.08)^{10}} = \$44,000$$

Table 14. Range of specific energy requirements for plasma destruction of typical waste materials (22).

Material	Specific Energy Requirement (SER) (kWH per pound)
PCBs	0.28 – 0.54
Medical waste	0.28 – 0.51
Municipal solid waste	0.35 – 0.70
Car fluff	0.43
Electric arc furnace dust	0.68 – 0.85
Automobile tires	0.85

4. Present Value of Capital Investment (V_p) is estimated as:

$$V_p = V - V_s = \$950,000 - \$44,000 = \mathbf{\$906,000}$$

5. Capital Recovery Cost (CRC) is estimated as:

$$CRC = \frac{(V - V_s) i (1 + i)^n}{(1 + i)^n - 1}$$

$$CRC = (950,000 - 44,000) \frac{0.08(1 + 0.08)^{10}}{(1.08)^{10} - 1} = (906,000) \frac{0.08(2.16)}{2.16 - 1}$$

$$CRC = \$134,963 \text{ per year capital recovery}$$

6. System Throughput is estimated as:

$$1,250 \text{ \#/hr.} \times 16 \text{ hrs./day} \times 21.25 \text{ days/mo.} = \mathbf{425,000 \text{ \#/mo.}}$$

7. Power Costs are estimated as:

$$0.40 \text{ kWh/\#} \times 5\text{¢/kWh} = 2.00\text{¢/\#}$$

8. Labor Costs are estimated as:

$$2 \times \$100,000/\text{yr.} \div 12 \text{ mo./yr.} \div 425,000 \text{ \#/mo.} = 3.92\text{¢/\#}$$

9. Maintenance Costs are estimated as:

$$\$20/\text{hr.} \div 1,250 \text{ \#/hr.} = 1.60\text{¢/\#}$$

10. Capital Amortization Costs (CAC) (Salvage Value taken into account) are estimated as:

$$\$134,963 \text{ \$/yr.} \div 12 \text{ mo./yr.} \div 425,000 \text{ \#/mo.} = 2.65\text{¢/\#}$$

11. Summary of Operating Costs:

a. Power Costs	2.00	¢/#
b. Labor Costs	3.92	¢/#
c. Maintenance Costs	1.60	¢/#
d. Equipment Amortization Cost	<u>2.65</u>	¢/#
	10.17	¢/#

Total Operating Costs = **\$203 /ton**

8 Technology Transfer Initiatives

Several technology transfer actions relating to the concept of plasma destruction of asbestos have taken place, particularly within the Department of Defense, since this two-phase CPAR program initially was awarded in June 1990. The following paragraphs describe the most applicable programs relating to the transfer of the technology developed in this CPAR project to the field.

Defense Logistics Agency (DLA)

In September 1992, The Defense National Stockpile Center (DNSC), DLA contacted USACERL to request information about the results of the Phase 1 CPAR program. Their principal interest was the disposal of approximately 5,500 tons of asbestos in their National Strategic Stockpile. This material is stored at seven locations in five states. Most of the asbestos is stored loose in oil storage tanks. The stockpile was created in the 1940s and 1950s.

The DLA request resulted in several meetings between DNSC and the Georgia Tech Construction Research Center, USACERL, and two CPAR industrial partners. At their request, DNSC was provided samples of vitrified asbestos for examination and testing.

In June 1993, DLA issued a solicitation for the final disposal of the initial 250 tons of amosite asbestos located at a site in Port Clinton, OH. Their proposed method of disposal was "plasma arc vitrification." In June 1994, the DLA awarded a competitive contract for this project to one of the CPAR partners, Plasma Technology Corporation (PTC). After an extensive period of investigating Federal, State, and local regulations to ensure that the project met all regulatory requirements, the project got underway in mid-1995. Figure 21 shows a diagram of the 500 kW plasma vitrification plant designed for this application.

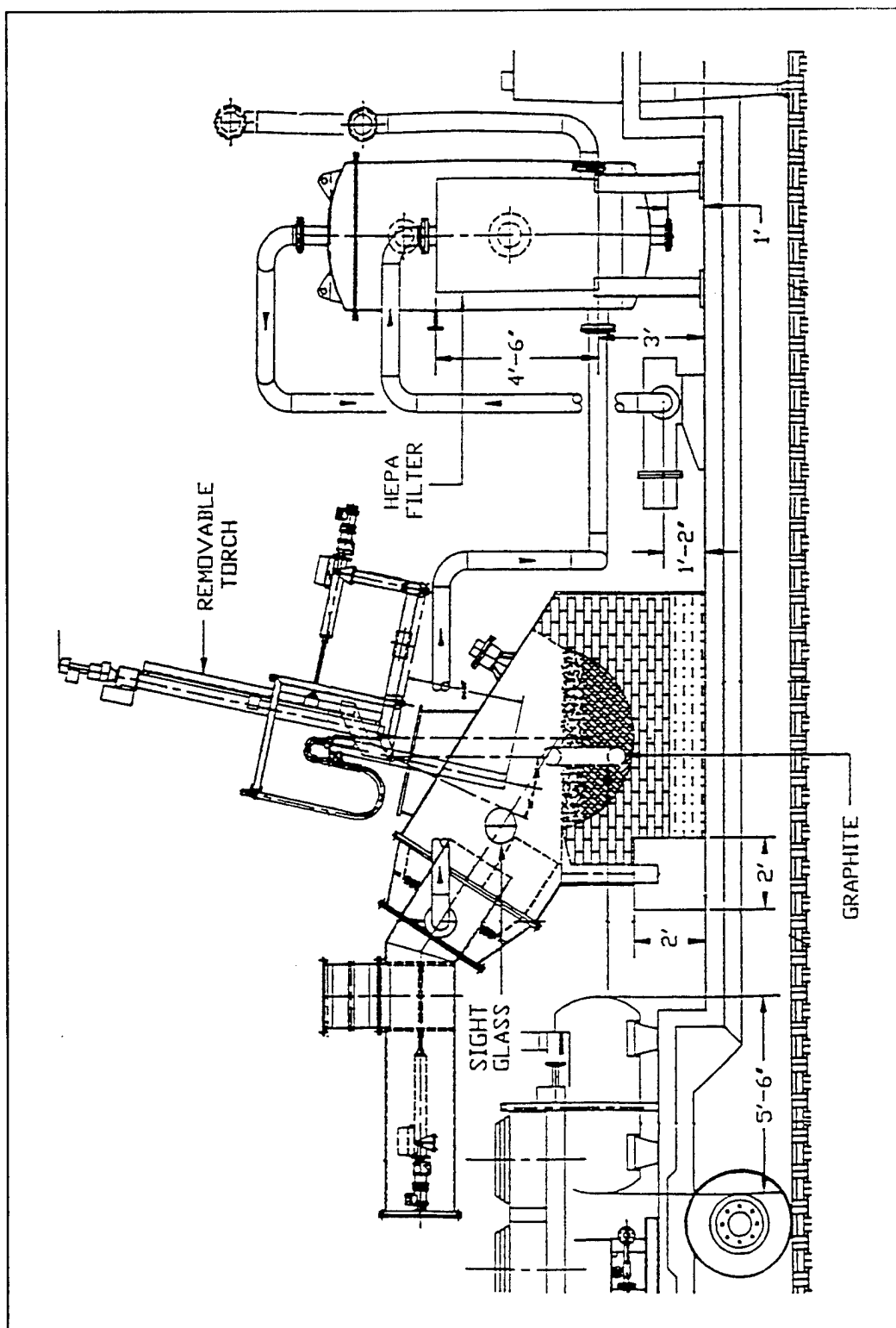


Figure 21. Plasma mobile asbestos vitrification plant.

The PTC system is distinctly different from the PAPS design criteria for several reasons, most significantly because:

1. The PTC system is designed for clean and pure bulk asbestos only.
2. PAPS will require a much more sophisticated feeding system than the simple screw feeder used for the DLA material.
3. The PAPS offgas treatment system must be designed to treat a much wider variety of offgases than the PTC system.
4. The PAPS system will require a secondary combustion system to combust the fuel gases given off by organic materials in the ACM.

During the Fall 1995, the plasma unit was set up and tested at the Port Clinton site. Before suspending the operation for the 1995-1996 winter season, the plant was processing 1,500 lb of asbestos per hour at a Specific Energy Requirement (SER) of approximately 500-600 kWh per ton. The fiber emission rate in the offgas is nondetectable. The vitrified, glassy, rock-like residue meets all EPA leachability criteria (Toxicity Characteristic Leaching Procedure [TCLP] tests). This residue material is planned to be sold as road gravel for \$8.00 per ton.

Rocky Mountain Arsenal, U.S. Army Materiel Command (USAMC)

Rocky Mountain Arsenal (RMA) near Denver, CO is an inactive production facility that has been previously used for the production of mustard gas, chlorine, pesticides, etc. A large effort for asbestos removal has been on-going for the past several years as part of a Superfund Site cleanup project. Estimated amounts of removed asbestos thus far are over 2 million lb that were landfilled. An additional 2 million lb are expected to be generated from the continuing asbestos removal effort. The asbestos is placed in double liner bags, loaded on trailers, and transported to a landfill site near Tooele Army Depot, UT.

In early 1993, USACERL was contacted by the RMA asbestos inspection team to provide information on the CPAR asbestos destruction program. Following several meetings between RMA, USACERL and Georgia Tech, RMA requested that the Construction Research Center conduct several plasma vitrification experiments on a variety of RMA asbestos-containing materials (ACM). These samples were contaminated with very low (nonhazardous) levels of chemical agents and pesticides. A series of eight experiments were conducted in 1994. The ACM consisted principally of tank/pipeline insulation, bonded wall and floor transite and plasters, and sealing materials. The plasma vitrification process was shown to reliably vitrify all asbestos samples into nonhazardous products. The vitrified residue readily

passed all EPA leachability TCLP tests. Initial economic indicators showed that the plasma processing costs would be favorable for contaminated asbestos and ACM. The results of this testing program are considered directly applicable to this CPAR program, and are discussed in more detail in Chapter 5 of this report (18).

Following this successful test program, RMA requested that the USACERL/Georgia Tech team develop a preliminary design for a 1 ton/hr plasma asbestos vitrification system to be located at Tooele Army Depot, UT. This "Tooele Plasma Applications Research Facility (TEPARF)" would be used to process asbestos from RMA and other military installations in the region. In addition, it would be used as a full-scale research facility to evaluate the potential of plasma technology to destroy other USAMC wastes. The preliminary design of the TEPARF and a NESHAP permit application package for the project were completed in July 1995. Figure 22 shows a schematic layout diagram of this design. In early 1995, RMA submitted a request to USAMC to fund the design, construction, and operation of the TEPARF for 5 years. Because of funding limitations, this project was not approved; its funding status remains uncertain.

Philadelphia Naval Shipyard

In January 1994, USACERL was contacted by the Facilities and Maintenance Department, Base Realignment and Closing (BRAC) Group, Philadelphia Naval Shipyard (PNS), whose primary interest was the plasma arc destruction of ACM generated as a result of the base closing activities. USACERL provided the BRAC group the results of the CPAR program up to that time to permit them to evaluate plasma technology and to conduct a "Type B" economic analysis.

Based on the PNS evaluation of using plasma technology to vitrify their ACM, BRAC funding was allocated to design and build a plasma asbestos vitrification plant at the base. In addition to the economic benefits of the process, the BRAC group determined that plasma vitrification of ACM would reduce government liability and the impact of environmentally required asbestos removal. The Naval Facilities Engineering Command (NAVFAC) contracted with an Architect-Engineer firm in Reading, PA to design a facility that would house the asbestos vitrification system and supporting equipment. The facility was designed to store, delag, bag, and vitrify the ACM taken from the Philadelphia Naval Base. The contractor also developed a separate performance specification for the design and construction of the plasma vitrification system. This specification included plasma heating system and furnace requirements, feeding and extraction mechanisms, and emission control systems.

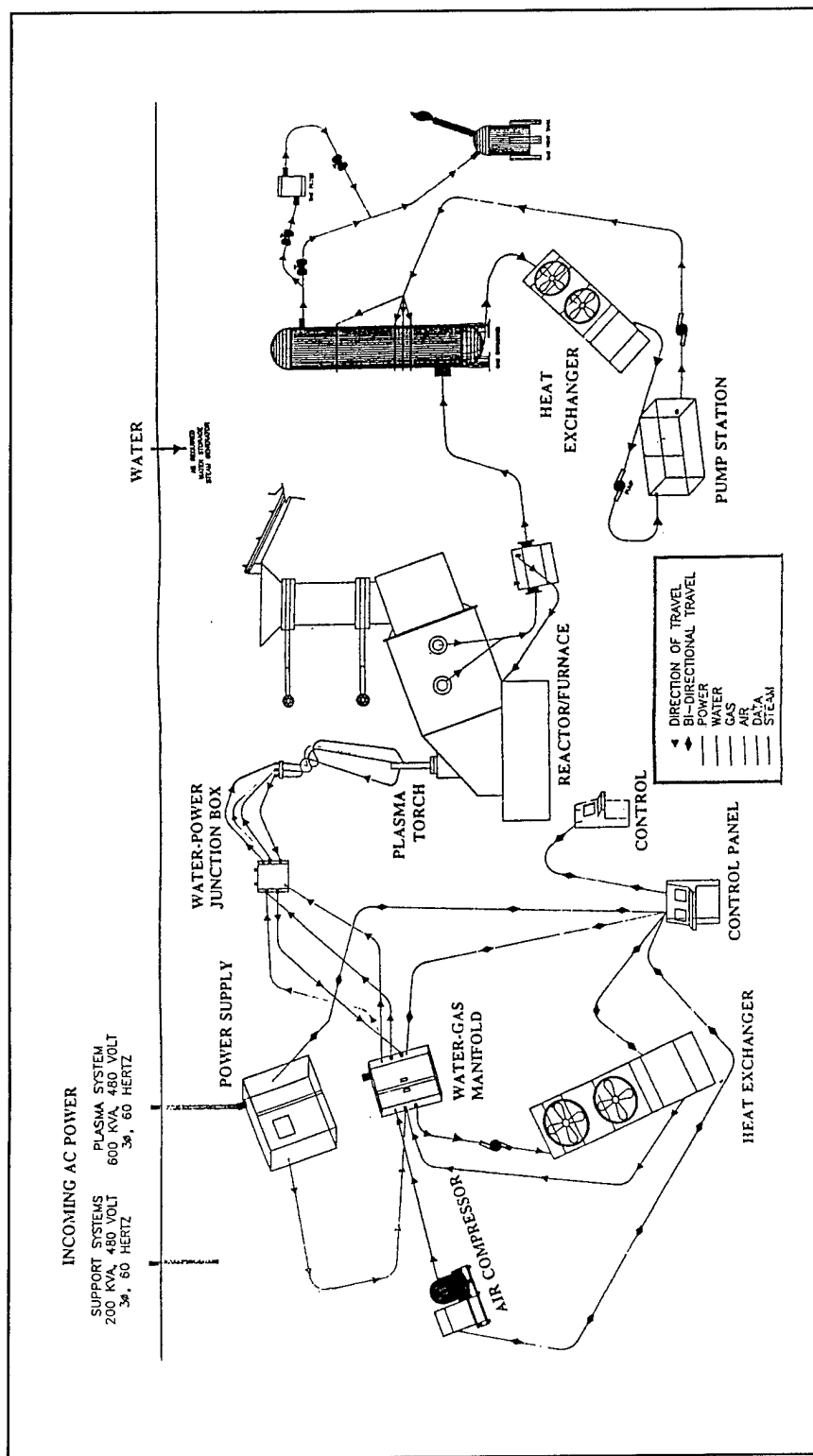


Figure 22. Schematic layout of the Tooele Plasma Applications Research Facility (TEPARF).

In the Fall of 1995, just before a NAVFAC competitive solicitation to design and build the plasma vitrification system, BRAC funding was reduced and this project was not funded. Funding for this project is presently on hold.

The EDF INERTAM Process

An associated ACM vitrification process was undertaken by Electricité de France (EDF) about the time that the Phase 1 CPAR asbestos destruction program was being completed. EDF began a series of tests on ACM in 1990. These experiments paralleled the CPAR program conclusions that asbestos and ACM could be safely and efficiently destroyed and vitrified using plasma arc technology.

Following these successful experiments, EDF created a subsidiary organization (INERTAM) in 1992, to design, build, and operate a mobile unit for the plasma vitrification of ACM. The mobile unit was completed and became operational in 1994. It is mounted on skids and can be transported on 20 trailers. The system includes five principal components (21):

1. An automated control system that allows the plant to be operated continuously by three personnel
2. A 1.75 MW transferred arc torch, produced by Aerospatiale
3. A reactor/furnace loading system that feeds 55-gal drums of ACM, two at a time, into the furnace
4. A high temperature furnace of 1 ton per hour capacity, and an associated secondary combustion system
5. A gas treatment system which includes a gas cooler, an acid gas neutralization system, and particulate filtration systems.

Figure 23 shows a schematic diagram of this process.

The INERTAM plant is processing ACM on site at an electrical generation plant being dismantled in Arjuzanx, France. The plant operates for 24 hours per day, 5 days a week. Approximately 100 tons per week of ACM are being processed. Volume reduction of the ACM is about 80 percent. The vitrified slag readily passes all French standard leachability requirements, and can be sold as road gravel. The offgas from the process complies with all European regulations concerning disposal of hazardous industrial waste.

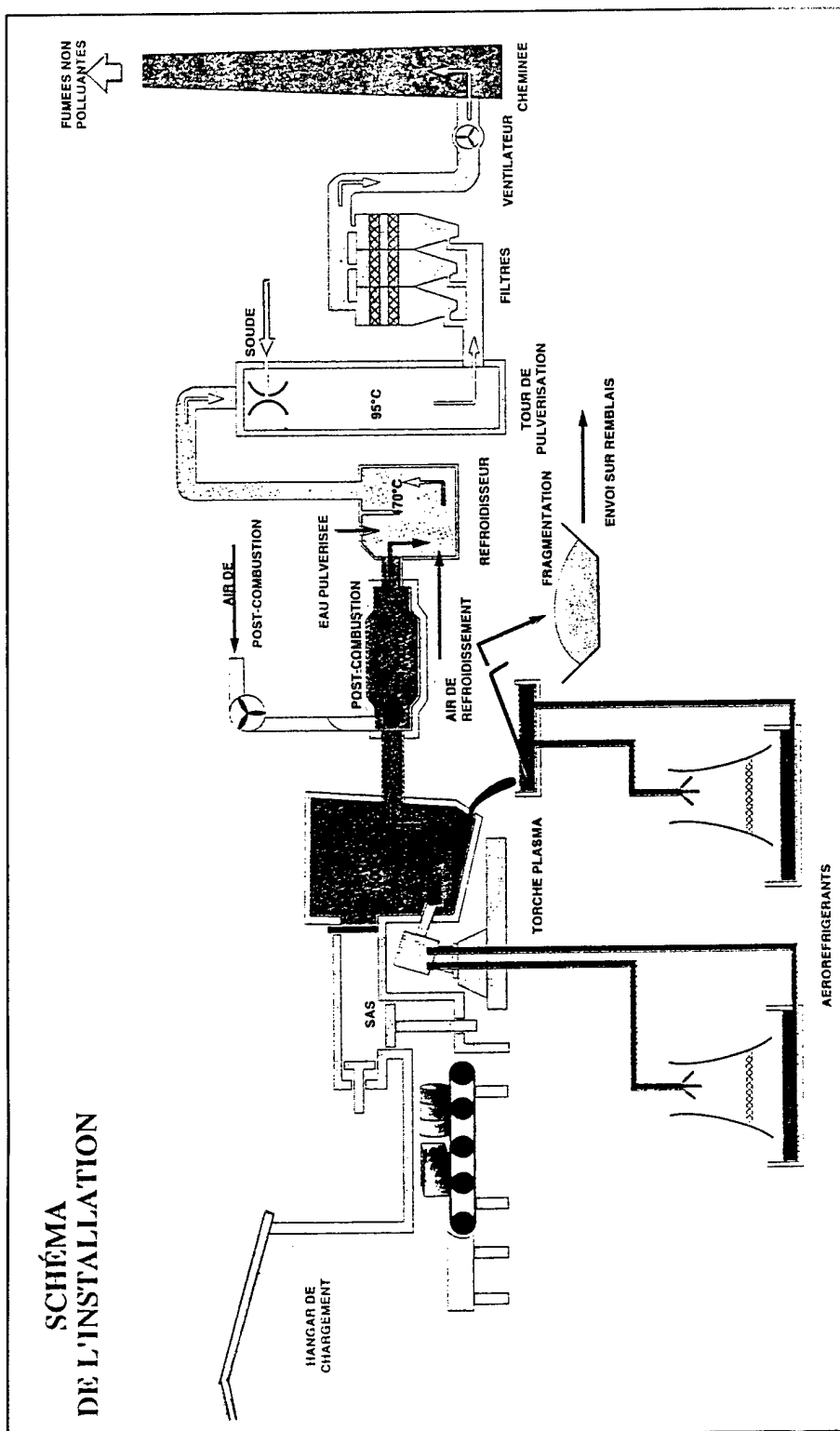


Figure 23. The INERTAM asbestos vitrification process.

Current Status

At the writing of this report, the DLA operation was still on-going after a long delay resulting from feed equipment freeze during the winter of 1996. The contract award was for a fixed sum, whereby the performing contractor was unable to release cost data prior to project completion. Both RMA and PNS projects were on hold awaiting pending funding from the U.S. Congress and VAVFAC, respectively. Both projects, however, had designs in various degrees of completion. Finally, the EDF INTRAM process completed processing all the waste in the original site at Arjuzanx, France, has been disassembled, and currently being re-located to a different site near Paris. The final report on the EDF asbestos vitrification project at Arjuzanx is not available at the time of writing this report, but all consensus indicate that it was both technically and economically successful; its sponsor is planning a second similar project, once the equipment is reassembled in the new location.

9 Summary and Conclusions

Summary

This study has demonstrated that ACM can be successfully processed into a harmless vitrified product, and has addressed the design criteria for a mobile Plasma Asbestos Pyrolysis System (PAPS) for on-site destruction of ACM, including a time schedule to develop and test an industrial-scale prototype system. This experimental program consisted of four separate experiments to vitrify various types of asbestos-containing materials (ACM):

- floor tile (2 types)
- transite wall board (1 type)
- roofing material (1 type).

These samples represented the most difficult ACM materials to destroy due either to the highly bonded character of the materials (floor tile and transite) or the high hydrocarbon content of the material (roofing). A 100 kW torch was used to process canisters of the ACM samples, which were individually loaded into a plasma furnace preheated to temperatures exceeding 1,400 °C. Processing temperatures ranged from 1,425 to 2,260 °C.

The experimental results indicated that a plasma arc torch can reliably destroy and vitrify a variety of ACM into nonhazardous products. The vitrified product passes full EPA Toxicity Characteristic Leaching Procedure (TCLP) analysis for hazardous organic and inorganic constituents. Physical inspection of the product revealed a brittle, nonhomogeneous material.

Elemental analysis of the vitrified product revealed six primary constituents, in descending amounts: silicon, calcium, aluminum, potassium, magnesium, and sodium. The product composition was largely dependent on ACM input composition. A combination of lower system vacuum pressures, greater torch height, and lower carrier gas pressures during initial sample injection provided for consistently less than 0.01 percent mass carryover.

Analysis of the particles in the exhaust gas stream revealed two modes of particle generation; an initial fragmentation of the ACM to produce larger particles (> 10 microns), and a vaporization of compounds from the melt to condense as smaller (0.5 to 2.0 microns) particles. The initial presence of a molten metal bath in the crucible appeared to reduce the loading of larger particles (> 10 microns) to the exhaust gas stream, but not contribute to the ACM processing rate or quality of the vitrified product. Heavily bound asbestos materials appeared to generate only slightly less particles in the exhaust. The vaporization/nucleation particle formation mode appears to be a potential hazard due to the vaporization of low vapor pressure heavy metals, and other metals salts. However, these were effectively treated in the scrubbing system.

Conclusions

This study concludes that:

1. When Asbestos-Containing Materials (ACM) are subjected to temperatures above 1,000°C, the asbestos fibers and the materials melt or pyrolyze and subsequently solidify (vitrify) into a nonhazardous, essentially inert solid material.
2. A mobile 1,250 lb per hour Plasma Asbestos Pyrolysis System (PAPS) can be developed using a 500 kW plasma heating system. The PAPS could be configured to fit on three 48-foot trailers. This system would be self-contained except for the need of an outside electrical power source. If necessary, a fourth trailer could contain an electrical generating system to make the system completely self-contained. The total time required to design, build and test a PAPS prototype system is estimated at 22 months.
3. ACM destruction and vitrification operating costs for a 1,250 lb per hour PAPS is estimated at \$203 per ton. These costs approximate the average ACM disposal costs at Class 1 EPA-approved landfills that comply with the National Emissions Standards for Hazardous Air Pollutants (NESHAP). These landfill disposal costs are expected to increase significantly as more restrictive disposal regulations are enacted.
4. Commercialization of an industrial scale PAPS system is available through any of the three industry partners that participated in this CPAR program.

5. The construction industry use for PAPS must be a selective decision based on specific economical and technical criteria. For the plasma arc technology application to be cost effective, a critical mass of ACM debris must be available in any new location before equipment mobilization. One major aspect to consider is the actual length of processing time requirement relative to total mobilization time requirements, including assembly and disassembly of the PAPS unit. In addition, both the quality and condition of the ACM also play an important role. Dry clean asbestos is easier and cheaper to vitrify. Moisture contents above 20 percent may present a cost on processing large amounts of water into vapor, therefore, wet ACM mixtures should be only considered if its moisture content could be appreciably reduced down to around 20 percent. Also, contaminated ACM with lead—or other EPA listed heavy metals—and/or chemical agents that may introduce stack emission problems, will have to be carefully studied and analyzed; their impact on the stack emission quality will have to be understood and safeguarded through alterations and modifications to the emissions treatment equipment. As with any other newly introduced technology, plasma arc technology has its “sweet spot” for application as well as its selection criteria for the most appropriate applications. USACERL and AEC will continue to work on User matrices guidelines and selection criteria.

Based on the results of the two consecutive phases of the asbestos destruction CPAR program, technology transfer within the DOD has already been initiated. The DLA has selected plasma arc technology to destroy the National Strategic Stockpile of amosite asbestos. The DLA awarded a contract to one of the CPAR research partners, and this partner has built a 500 kW system, similar to PAPS, which has begun this task. The U.S. Army Materiel Command, Rocky Mountain Arsenal has developed a preliminary design concept to establish a plasma facility at Tooele Army Depot, UT to destroy contaminated asbestos. The U.S. Naval Facilities Engineering Command is also strongly considering plasma arc technology to process and destroy the asbestos wastes at Naval bases being closed.

Outside the United States, the French utility company, Electricité de France (EDF) has built and is operating a 1.75 MW system to destroy 20 tons of ACM per day from a power generation plant in Arjuzanx, France that is being dismantled. The increasing popularity of plasma arc technology as an asbestos and ACM thermal destruction option highlights the successful transfer of CPAR-developed technology. It is indicative of the potential of plasma arc technology to destroy ACM in an environmentally safe, efficient, and cost-effective manner.

Mode of Commercialization and Technology Transfer

Commercialization of an industrial scale PAPS system is available through USACERL industrial partners that participated in this CPAR program. Unit prices may vary with size, feed rate, and the demands placed on the complexity of the emission scrubbing equipment. In general, a lead time of 6 months is necessary to order, build, integrate, and finally "shake down" and test a new plasma arc unit. The main point of contact (POC) for asbestos destruction applications is Dr. Lou Circeo at GTRI, phone: (404) 894-2070; Fax: (404) 894-1989.

Payment schedules and delivery terms vary depending on the manufacturer of the main components and the performance level of the auxiliary systems. Various plasma torch manufacturers produce torches with different configurations; all manufacturers tend to recommend their specific equipment for use in any given or suggested application. Therefore, it is highly recommended that the equipment procurement process begin with the support of a reputable system integrator, a third party industrial design, or an entity with both prior experience in the required application and a track record of success performing the services needed within the targeted specifications. Currently, several Federally funded plasma projects for a variety of applications besides asbestos, have matured to the point where a Federal Plasma Users Group (FPUG) was instituted for the purposes of pooling, sharing, and finally disseminating project information and data on timely basis. The POC for the FPUG at USACERL is Dr. Edgar Smith, phone: (217) 373-3488; Fax: (217) 373-3490.

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Appendix A: Elemental Composition and Decomposition of Asbestos

1. Elemental Composition of Asbestos

- a. Chrysolite - $\text{Mg}_3[\text{Si}_2\text{O}_5](\text{OH})_4$
- b. Crocidolite - $\text{Na}_2\text{Fe}^{2+}_3\text{Fe}^{3+}_2[\text{Si}_8\text{O}_{10}](\text{OH})_2$
- c. Anthophyllite - $(\text{Mg},\text{Fe}^{2+})_7[\text{Si}_8\text{O}_{22}](\text{OH},\text{F})_2$
- d. Cummingtonite-Grunerite - $(\text{Mg},\text{Fe}^{2+},\text{Mn})_7[\text{Si}_8\text{O}_{22}](\text{OH})_2$
- e. Tremolite-Ferroactinolite - $\text{Ca}_2(\text{Mg},\text{Fe}^{2+})_5[\text{Si}_8\text{O}_{22}](\text{OH},\text{F})_2$

2. Asbestos Decomposition Products

- a. Hematite - Fe_2O_3
- b. Magnesioferrite - $\text{MgFe}_2^{3+}\text{O}_4$
- c. Actinolite - $\text{Ca}_2(\text{Mg},\text{Fe}^{2+})_5[\text{Si}_8\text{O}_{22}](\text{OH},\text{F})_2$
- d. Quartz - SiO_2
- e. Forsterite - Mg_2SiO_4
- f. Enstatite - $(\text{Mg},\text{Fe}^{2+})[\text{SiO}_3]$ - a specific orthopyroxene
- g. Orthopyroxene - $(\text{Mg},\text{Fe})[\text{SiO}_3]$ - a subset of the pyroxenes
- h. Diopside - $\text{Ca}(\text{Mg},\text{Fe})[\text{Si}_2\text{O}_6]$
- i. Talc - $\text{Mg}_3[\text{Si}_4\text{O}_{10}](\text{OH})_2$
- j. Cummingtonite - $(\text{Mg},\text{Fe}^{2+},\text{Mn})_7[\text{Si}_8\text{O}_{22}](\text{OH})_2$
- k. Pyroxene - $(\text{Ca},\text{Fe},\text{Mg})_2\text{Si}_2\text{O}_6$

Appendix B: Features and Benefits of Plasma Heating Systems

Massless Heat

Plasma arc torches use only a small fraction of the air needed by fossil fuel heaters. Releasing heat energy with almost no mass is a simpler process than conventional heating and offers greater control and efficiency. It also reduces furnace fabrication expenses, off-gas-handling, and other capital costs because plasma arc torches operate in smaller furnaces than fossil fuel heaters.

Higher Temperatures

Plasma arc torches operate efficiently at temperatures well beyond those possible with fossil fuel burners. They can routinely create temperatures that range from 4,000-7,000 degrees centigrade or higher. This extreme heat is produced instantly, and can be easily automated. Controlled, high temperatures increase throughput and reduce costs.

Controlled Furnace Atmosphere

Plasma arc torches operate with almost any gas or gas mixtures (oxidizing, reducing, inert, etc.). This flexibility means the furnace atmosphere is completely variable, and can be tailored to satisfy the individual processing environment.

High Thermal Efficiency

The efficiency of plasma arc torches consistently reaches between 85% and 93%. Therefore, the faster and more complete reaction kinetics of plasma energy sharply reduces turnaround time and operating costs.

Efficiency and Safety

Because the plasma column is rigidly controlled, plasma arc torches can direct heat at specific surfaces. Intense heat is available instantly and temperature control is easily automated. Torch configurations vary to suit the exact processing needs. The plasma arc flame can be extinguished quickly. Numerous safety and monitoring features are designed into the plasma torch control panels to ensure maximum safety, efficiency, and control

In the steel industry, Plasma Tundish Heating helps reduce melting and casting costs, and improves product quality. Plasma heating systems control the temperature of the steel directly in the tundish and/or the ladle. Such precise temperature control results in more uniform cast structures, improves the continuous casting process, reduces downtime, lowers temperature requirements for casters, allows casting in narrower temperature zones, and increases productivity.

Productivity

Plasma heating systems ionize gases to convert electricity into heat. They operate with almost any gas including air, argon helium, hydrogen, CO₂, or CH₄. For added flexibility, they can also operate with many gas mixtures. Many configurations are available, from low power convertible torches (which are perfect for research laboratories) to the high power systems suitable for vacuum processing.

Plasma Arc Torches

Plasma arc torches can be adapted for almost any operating requirements. All of these torches benefit from the same positive features of plasma energy, and are available in many sizes, ranging from about 100 kilowatts to 10 megawatts.

Transferred Arc Torches

A transferred arc torch uses the working material to conduct electricity. Its positive polarity is in the work piece. The result is an intense, direct heat that is ideal for melting smelting gasification, annihilation, recovery, and reclamation.

Nontransferred Arc Torches

A nontransferred arc torch uses two internal electrodes. A small column of injected gas creates the plasma flame that extends beyond the tip of the torch. A non-transferred torch produces the more dispersed heat that is needed for air and gas heating, drying, annealing solid particle ignition, cutting, and for processing high temperature, non-conductive materials like glass and ceramics.

Convertible Arc Torches

Convertible arc torches can operate in either the transferred or nontransferred mode. Field conversion is quick, easy, and has significant advantages in research applications.

Variable Electrode Materials

Plasma arc torches offer a selection of electrode materials for complete process compatibility: copper, tungsten, molybdenum, certain alloys, and others. With this selection of electrode materials, greater strength is available, process contamination is controlled, and cost is minimized. Once expended, these electrodes are easily replaced.

Introduction

In today's industrial and commercial environments, new processing methods are essential for growth and productivity. Until recently, heat processing was typically limited to conventional fuel combustion, but advancements in heating technology now offer more efficient options. One of the proven alternatives for generating heat is the plasma arc heating system, a high technology product of intensive research, practical experience, industrial demands, and aerospace technology. Plasma heating systems are among the most effective means for efficiently generating heat. They far surpass conventional methods because they offer greater temperature control, faster reaction time, better processing control, lower capital costs, greater throughput, and more efficient use of energy. The applications for plasma heating systems are widespread, ranging from industrial and research environments to municipal waste management. They include ladle and tundish heating melting (ferrous and nonferrous metals), vacuum melting, recovery processes, municipal and hazardous waste treatments, and chemical synthesis.

Plasma energy is a common, naturally-occurring resource. It is the most prevalent state in the universe. Simply stated, plasma energy is any gas that conducts or can be made to conduct electricity. The discharged static electricity in thunderstorms (lightning) is an example of plasma energy, and so is the aurora borealis, or "Northern Lights." Plasma heating technology has a proven record of success in certain industrial applications. Over 30 years ago, plasma heating technology was used in the space program to simulate the torrid temperatures of re-entry into the earth's atmosphere. Today, plasma heating systems continue to demonstrate their strength in a wide variety of industrial and commercial environments.

Plasma Energy Applications

Plasma energy technology is a valuable resource for many commercial environments, including steel mills, reactive metal industries' municipal/hazardous waste disposal sites, and research laboratories. As a controlled, high-intensity, and reliable heat source, plasma heating systems can be used in vacuum furnaces for titanium processing, as gas heaters for drying, heat treatment, or preheating, in glass/ceramic processing, and for coal gasification. They can also be used for bulk melting, smelting, pyrolysis, precious metal recovery, or other extractive metallurgical processes. Plasma heating systems offer exciting options for refining refractory metals and for processing metals in high purity environments. During processes like cold-crucible and cold-hearth melting, plasma-heating systems deliver the controlled concentrated energy that ensures purity, homogeneity, and controlled solidification. This technology can also be applied to scrap recycling and ceramic synthesis.

Appendix C: PM-10 Exhaust Gas Particle Loading

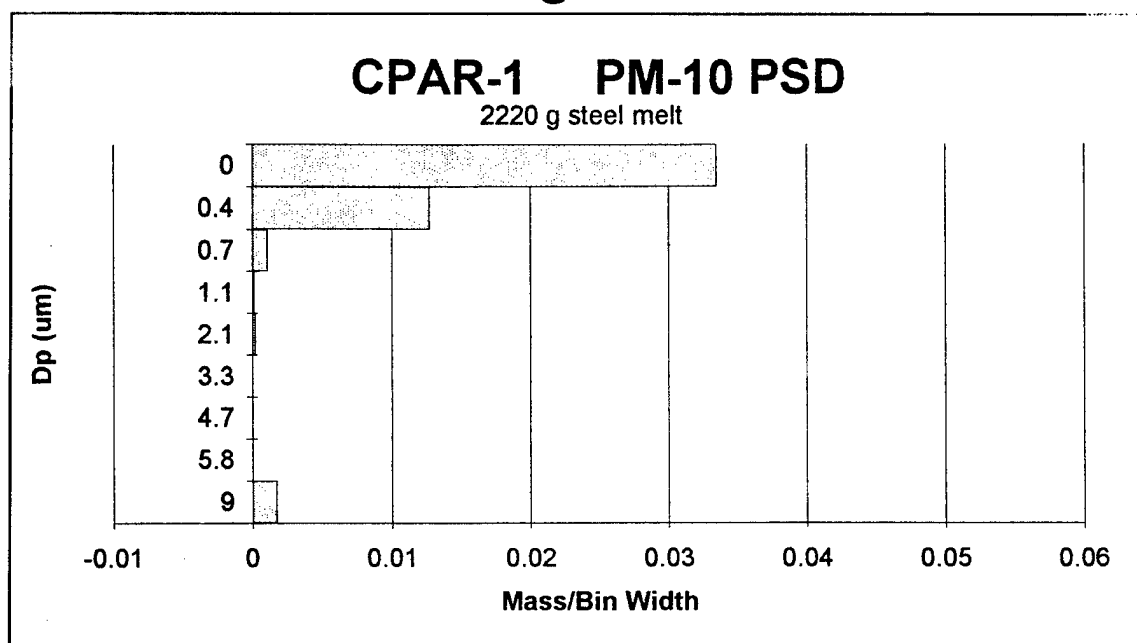


Figure C1. PM-10 exhaust gas particle loading: 2220 g steel melt.

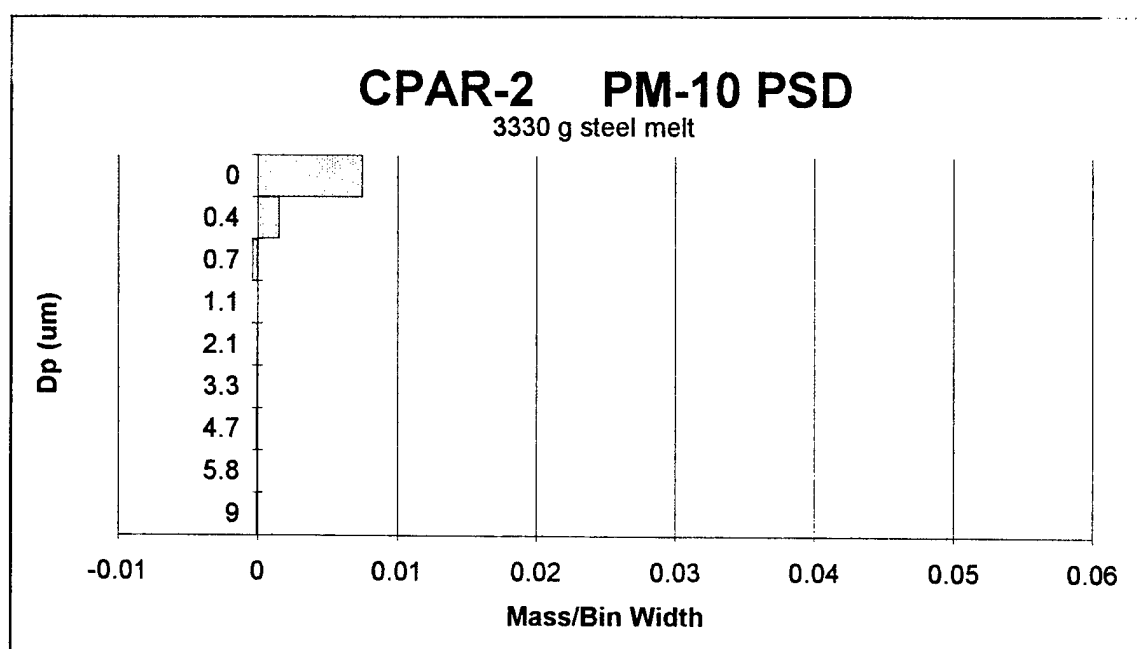


Figure C2. PM-10 exhaust gas particle loading: 3330 g steel melt.

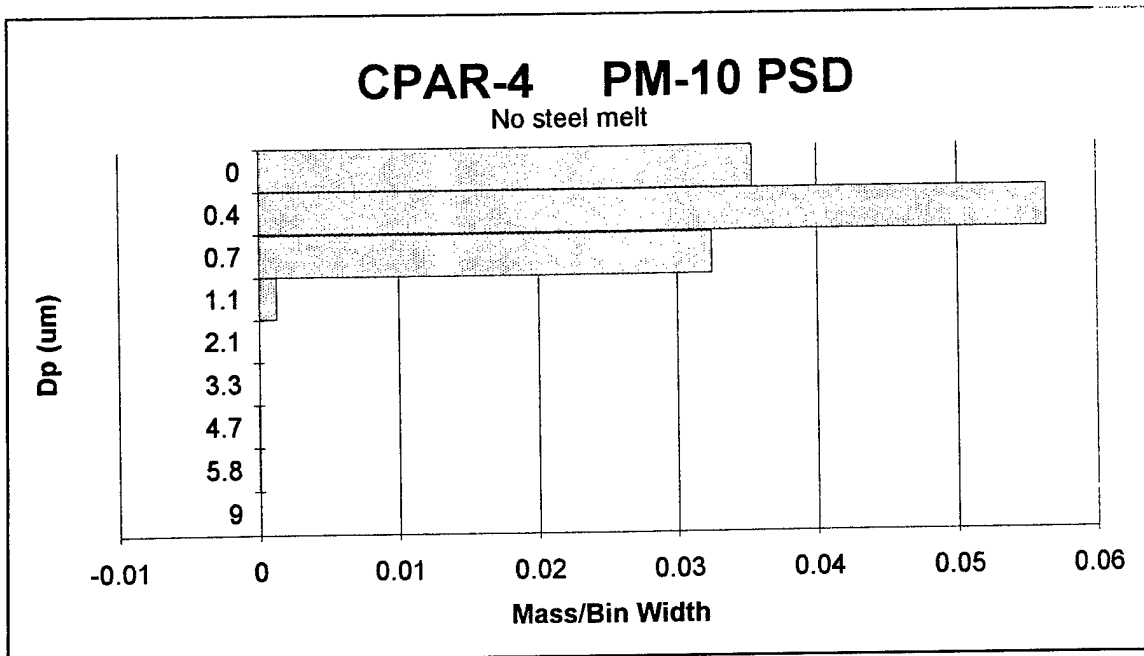
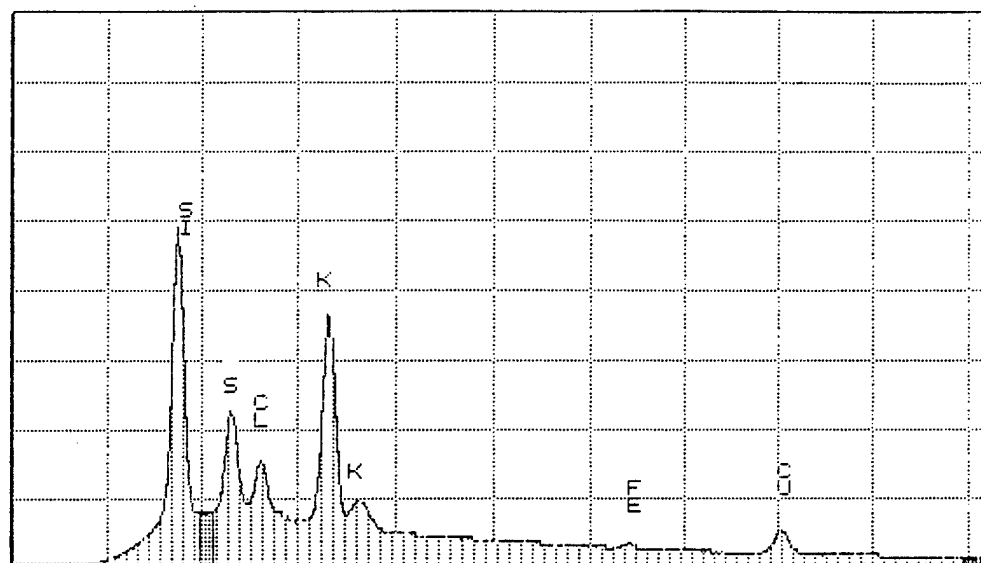


Figure C3. PM-10 exhaust gas particle loading: no steel melt.

Appendix D: Elemental Absorption - Cascade Impactor

Cursor: 0.000keV = 0

ROI (1) 9.940:10.180



0.000

VFS = 16384 10.240

201

CPAR-1

SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-1
EL NORM. K-RATIO

SI-K 0.27590 +- 0.00129
K -K 0.33451 +- 0.00165
FE-K 0.00200 +- 0.00019
CU-K 0.18967 +- 0.00255
CL-K 0.06442 +- 0.00068
S -K 0.13347 +- 0.00095

ZAF CORRECTION 20.00 KV 76.80 Deqs

No. of Iterations 2

	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
SI-K	0.275	0.961	1.270	0.988	1.206	36.53	28.26
K -K	0.334	1.004	1.148	0.998	1.152	30.37	32.72
FE-K	0.002	1.076	1.030	0.963	1.068	0.12	0.18
CU-K	0.189	1.117	1.010	1.000	1.129	10.28	18.18
CL-K	0.064	1.000	1.273	0.978	1.247	7.06	6.82
S -K	0.133	0.968	1.282	0.982	1.220	15.64	13.83

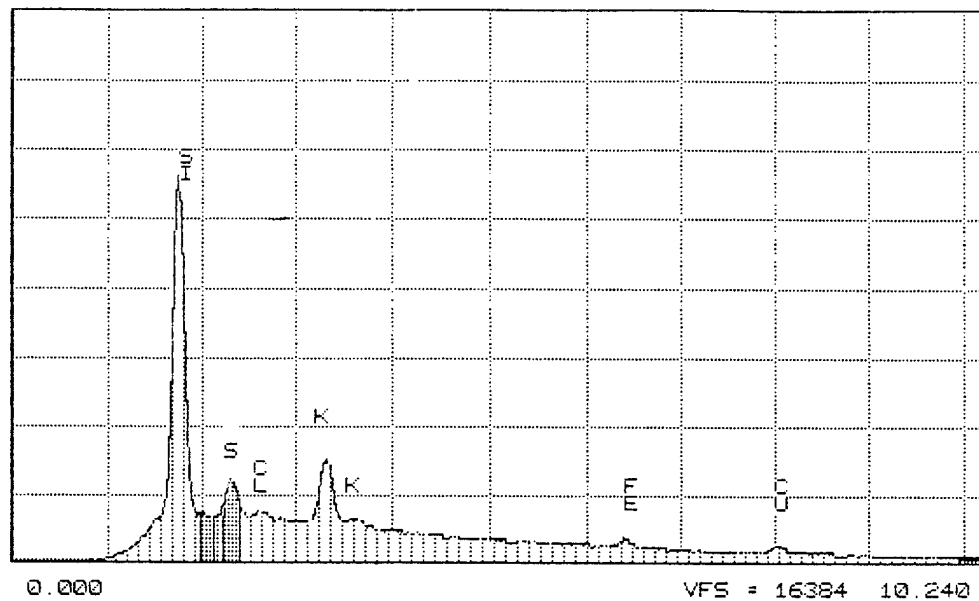
* - High Absorbance

SSQ:

Figure D1. Elemental absorption—cascade impactor, experiment CPAR 1.

Cursor: 0.000keV = 0

ROI (1) 9.540:10.180



SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-2
EL NORM. K-RATIO

SI-K 0.59525 +- 0.00252
K -K 0.18556 +- 0.00163
FE-K 0.03568 +- 0.00111
CU-K 0.10611 +- 0.00253
CL-K-0.00000 +- 0.00000
S -K 0.07738 +- 0.00096

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 2

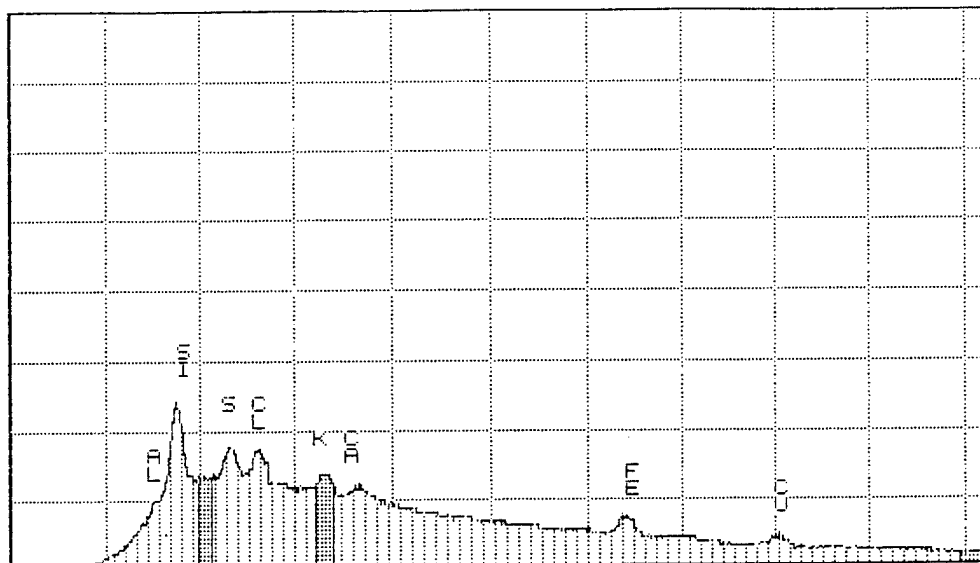
	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
SI-K	0.595	0.976	1.175	0.994	1.141	67.53	58.07
K -K	0.185	1.021	1.162	0.998	1.185	15.70	18.80
FE-K	0.035	1.097	1.022	0.977	1.096	1.94	3.34
CU-K	0.106	1.139	1.009	1.000	1.149	5.31	10.43
CL-K	0.000	1.018	1.356	0.968	1.365	0.00	0.00 G
S -K	0.077	0.984	1.446	0.993	1.414	9.52	9.36 *

* - High Absorbance

SSQ:

Figure D2. Elemental absorption—cascade impactor, experiment CPAR 2.

Cursor: 0.000keV = 0 FOI (1) 9 940:10.180



0.000

VFS = 8192 10.240

200

CPAR-3

SSD

SEMI-QUANTITATIVE ANALYSIS: CPAR-3
EL NORM. K-RATIO

SI-K 0.14669 +- 0.00230
K -K 0.10884 +- 0.00230
FE-K 0.21675 +- 0.00504
CU-K 0.24746 +- 0.00709
CL-K 0.08080 +- 0.00186
S -K 0.10602 +- 0.00206
CA-K 0.09341 +- 0.00219
AL-K-0.00000 +- 0.00000

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 2

----	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %	
SI-K	0.146	0.942	1.451	0.991	1.356	25.48	17.32	*
K -K	0.108	0.983	1.150	0.983	1.113	11.14	10.55	
FE-K	0.216	1.052	1.022	0.961	1.034	14.36	19.53	
CU-K	0.247	1.090	1.020	1.000	1.113	15.43	23.99	
CL-K	0.080	0.980	1.261	0.987	1.221	10.11	8.59	
S -K	0.106	0.949	1.290	0.986	1.209	14.37	11.16	
CA-K	0.093	0.961	1.141	0.990	1.087	9.11	8.85	
AL-K	0.000	0.971	1.774	0.990	1.706	0.00	0.00	G *

* - High Absorbance

SSD:

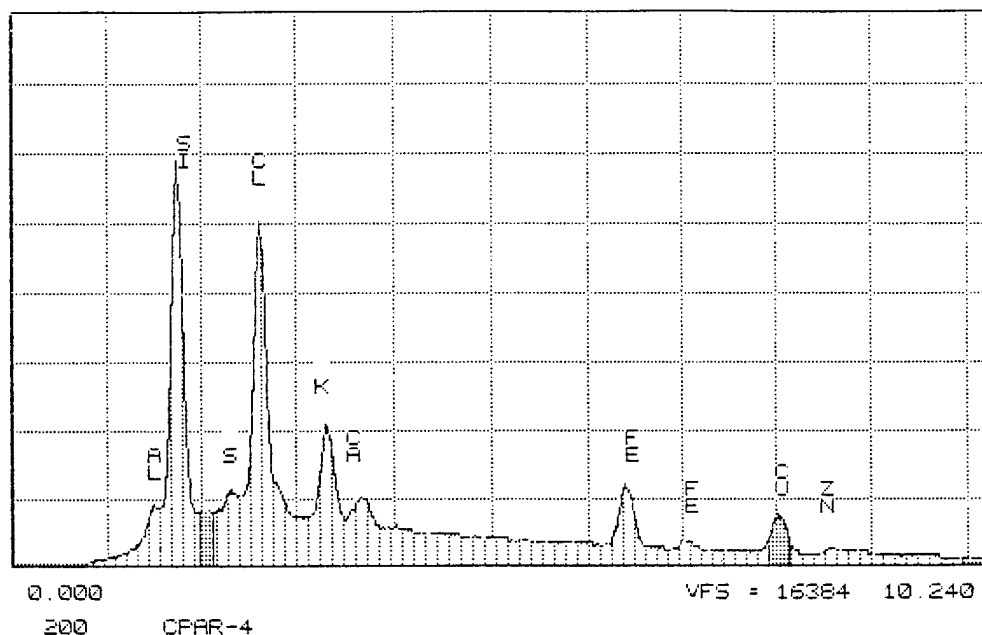
D-3

Figure D3. Elemental absorption—cascade impactor, experiment CPAR 3.

Cursor: 0 000keV = 0

ROI

(1) 9 340:10.180



SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-4
EL NORM. K-RATIO

SI-K 0.22055 +- 0.00091
K -K 0.09650 +- 0.00070
FE-K 0.16192 +- 0.00141
CU-K 0.20731 +- 0.00211
CL-K 0.22939 +- 0.00101
S -K 0.01758 +- 0.00027
CA-K 0.02678 +- 0.00038
AL-K 0.00000 +- 0.00000
ZN-K 0.03984 +- 0.00101

ZAF CORRECTION 20.00 KV 75.80 Degs

No. of Iterations 2

---	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %	
SI-K	0.220	0.945	1.404	0.991	1.316	34.85	24.82	*
K -K	0.096	0.987	1.186	0.992	1.163	9.68	9.60	
FE-K	0.161	1.057	1.021	0.960	1.037	10.08	14.35	
CU-K	0.207	1.095	1.016	1.000	1.114	12.13	19.74	
CL-K	0.229	0.984	1.221	0.991	1.191	26.23	23.35	
S -K	0.017	0.952	1.321	0.978	1.231	2.27	1.85	
CA-K	0.026	0.964	1.164	0.992	1.115	2.51	2.55	
AL-K	0.000	0.973	1.706	0.986	1.639	0.00	0.00	G *
ZN-K	0.039	1.080	1.012	1.000	1.093	2.25	3.72	

* - High Absorbance

SSQ:

D-4

Figure D4. Elemental absorption—cascade impactor, experiment CPAR 4.

Appendix E: Optical Pyrometer Data - Temperature

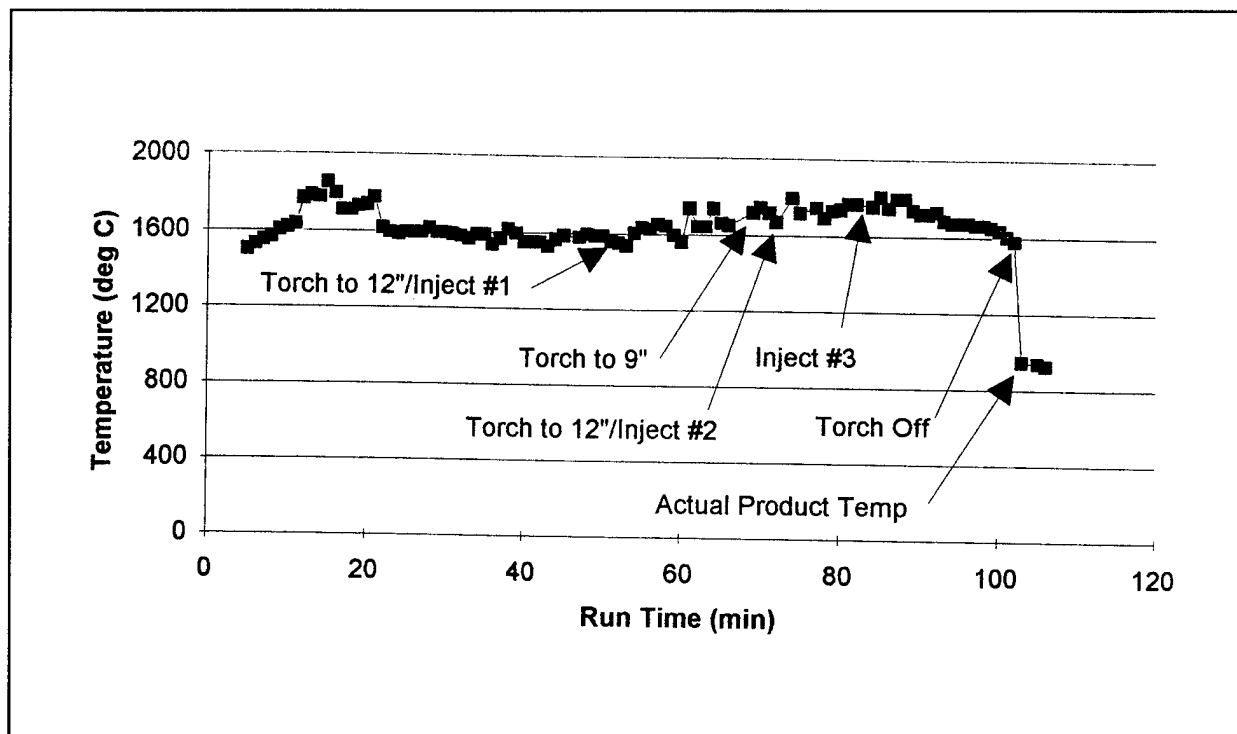


Figure E1. Optical pyrometer data—temperature, experiment CPAR 1.

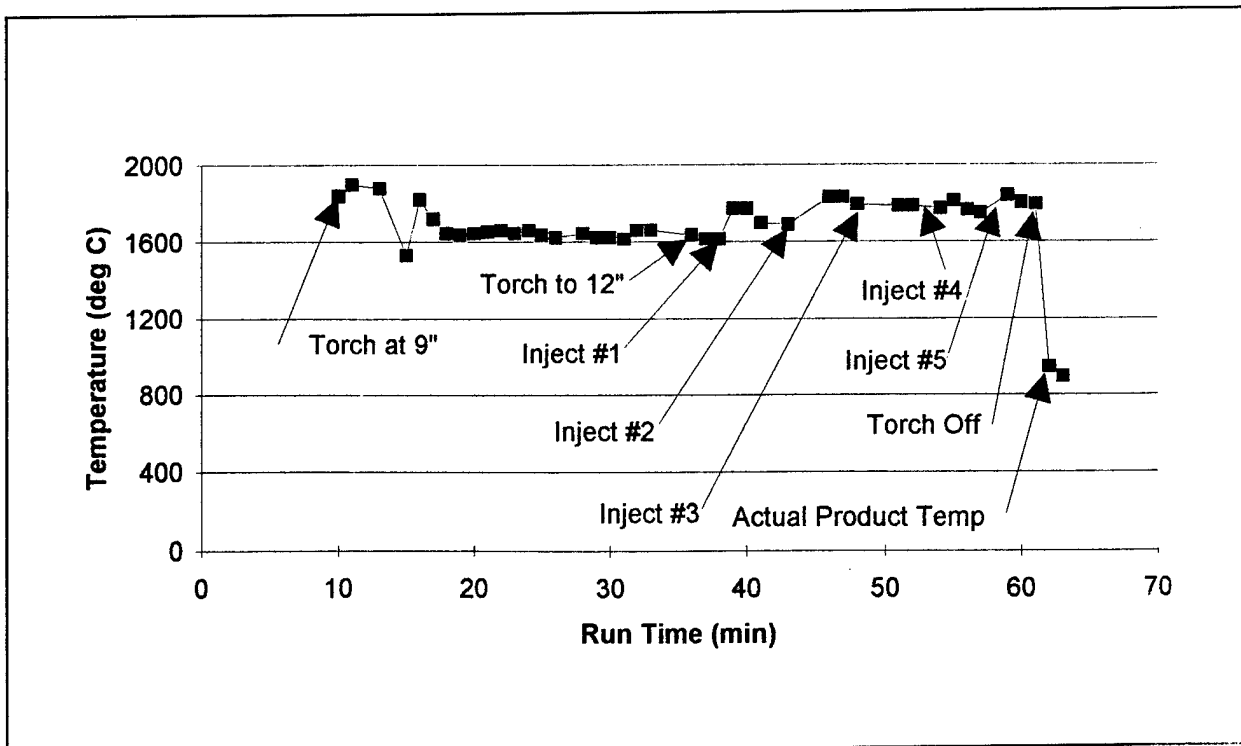


Figure E2. Optical pyrometer data—temperature, experiment CPAR 2.

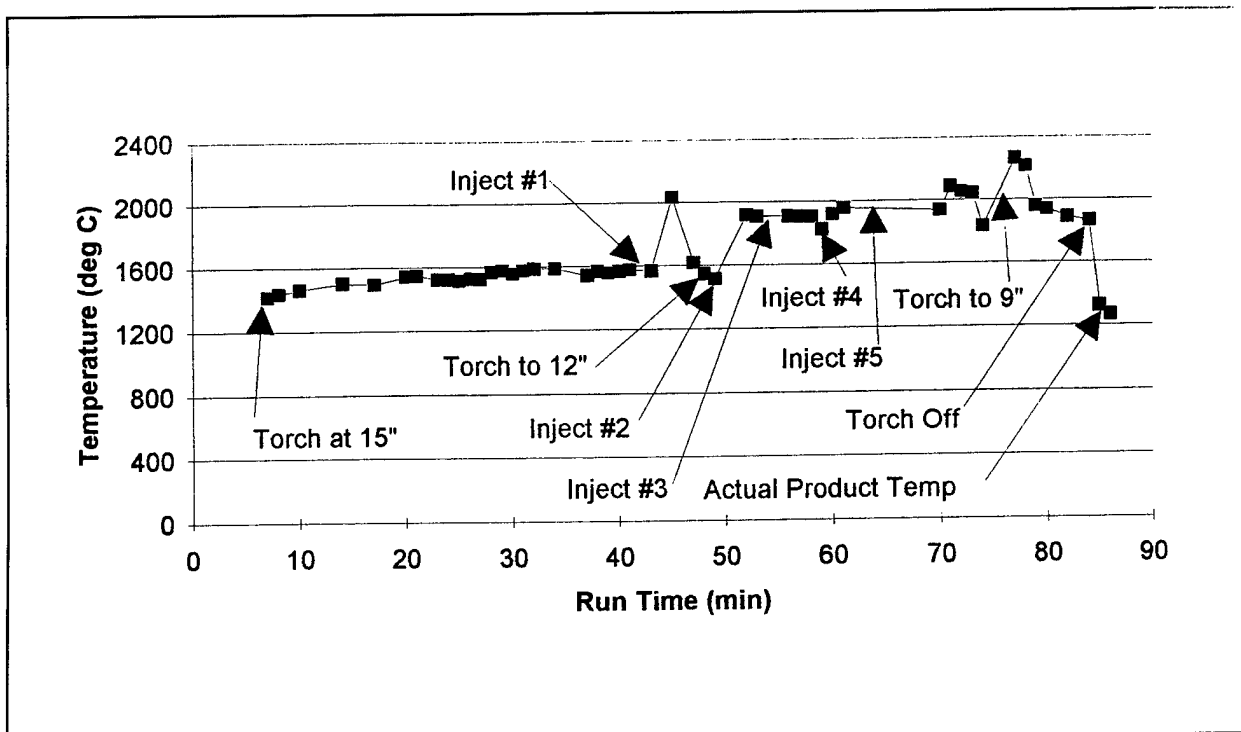


Figure E3. Optical pyrometer data—temperature, experiment CPAR 3.

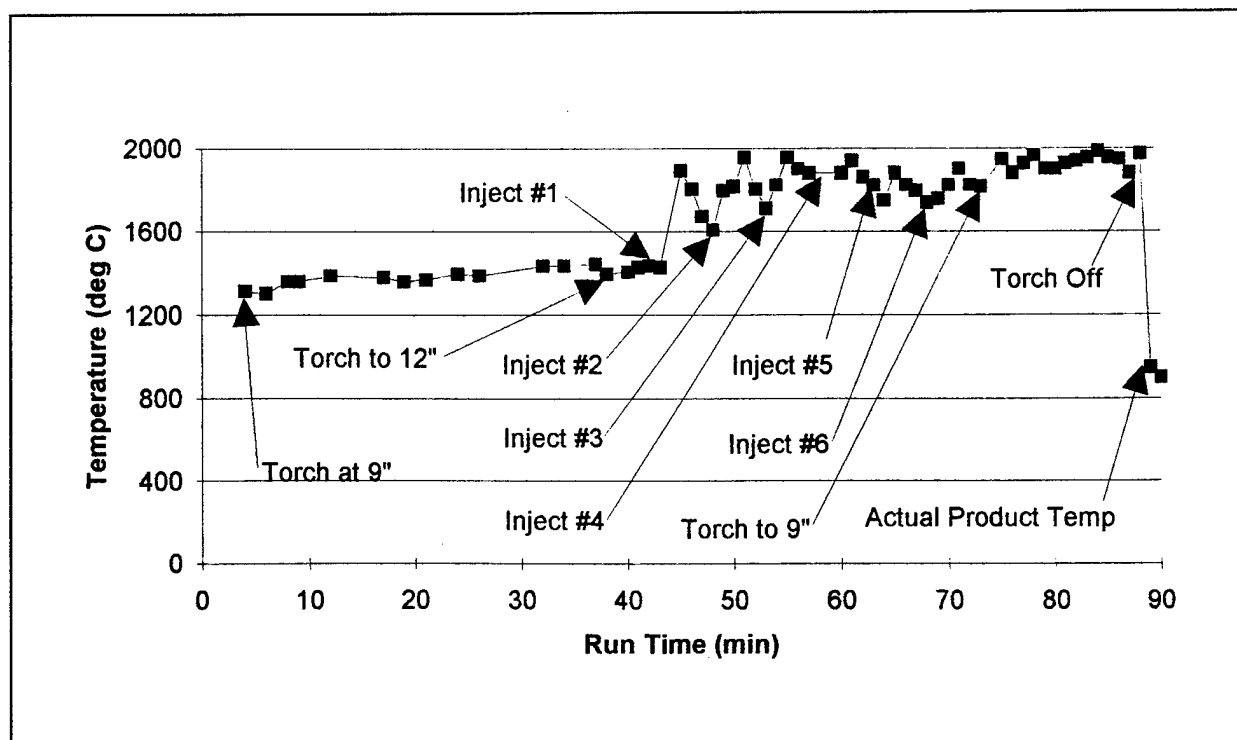
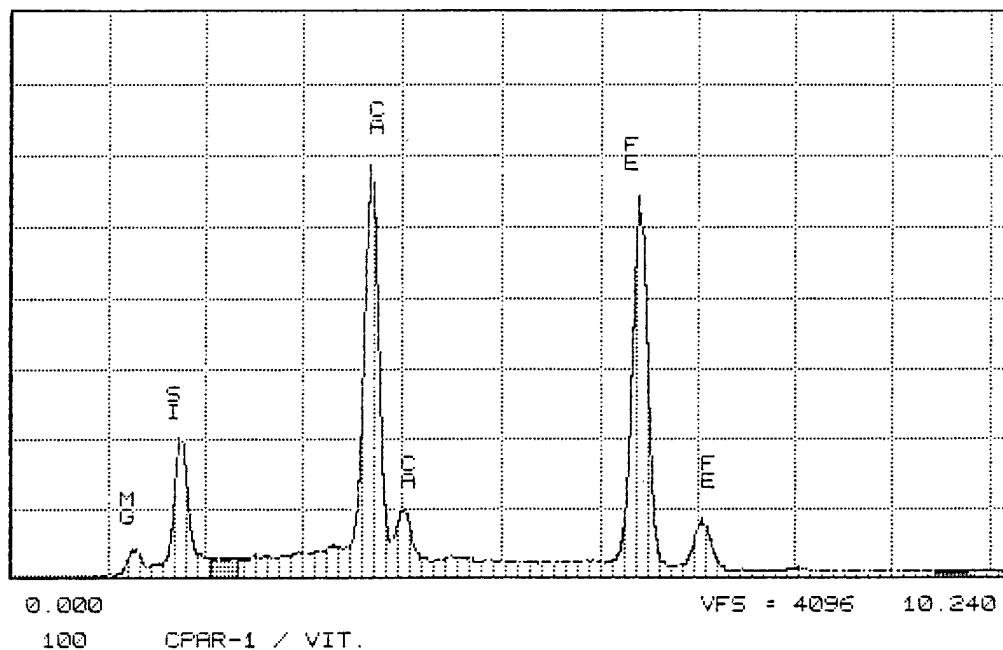


Figure E4. Optical pyrometer data—temperature, experiment CPAR43.

Appendix F: Elemental Absorption - Vitrified Product

Cursor: 0.000keV = 0

ROI (1) 9.440: 9.800



SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-1 / VIT.
EL NORM. K-RATIO

CA-K 0.27491 +- 0.00140
FE-K 0.66630 +- 0.00329
SI-K 0.05071 +- 0.00050
MG-K 0.00806 +- 0.00022

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 2

	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
CA-K	0.274	0.948	1.047	0.970	0.964	29.39	25.03
FE-K	0.666	1.036	1.017	1.000	1.054	55.64	66.34
SI-K	0.050	0.930	1.554	0.996	1.441	11.58	6.90 *
MG-K	0.008	0.922	2.472	0.998	2.275	3.39	1.73 *

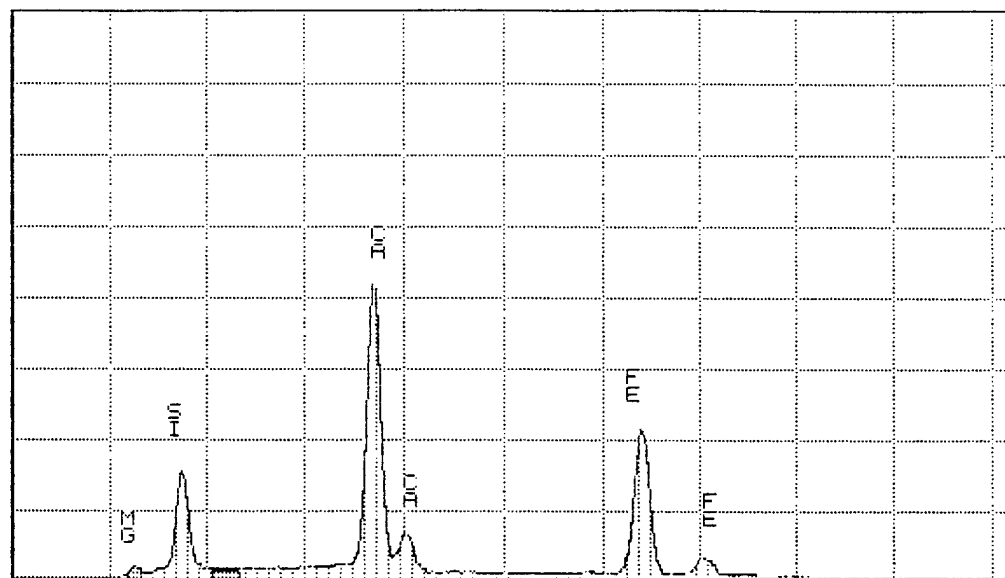
* - High Absorbance

SSQ:

Figure F1. Elemental absorption—vitrified product, experiment CPAR 1.

Cursor: 0.000keV = 0

ROI (1) 9.440: 9.800



0.000

100

CPAR-2 / VIT.

VFS = 8192

10.240

SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-2 / VIT.
EL NORM. K-RATIO

CA-K 0.39139 +- 0.00166
FE-K 0.52412 +- 0.00290
SI-K 0.07991 +- 0.00062
MG-K 0.00516 +- 0.00017

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 1

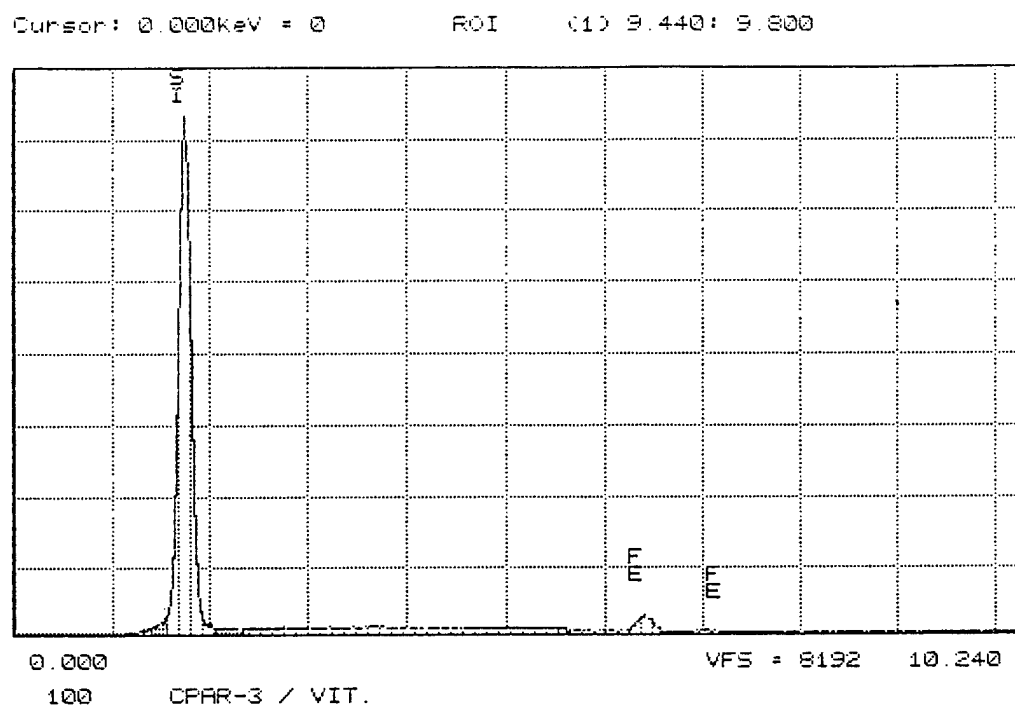
----	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
CA-K	0.391	0.960	1.044	0.978	0.981	39.90	35.91
FE-K	0.524	1.050	1.025	1.000	1.077	41.90	52.79
SI-K	0.079	0.941	1.477	0.995	1.384	16.30	10.27 *
MG-K	0.005	0.933	2.277	0.996	2.119	1.90	1.02 *

* - High Absorbance

SSQ: SSETUP

SSQ:

Figure F2. Elemental absorption—vitrified product, experiment CPAR 2.



SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-3 / VIT.
EL NORM. K-RATIO

FE-K 0.11971 +- 0.00205
SI-K 0.88028 +- 0.00308

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 5

	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
FE-K	0.119	1.113	1.012	1.000	1.126	6.65	12.46
SI-K	0.880	0.988	1.090	0.999	1.077	93.35	87.54

* - High Absorbance

SSQ: SSQSETUP SEVE\5

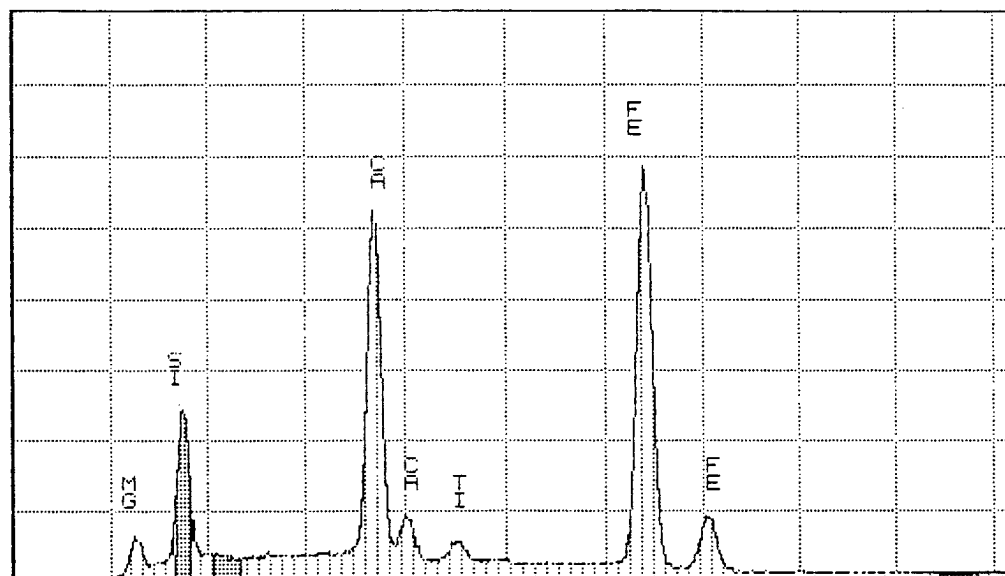
SSQ: SETUP SSQ

SSQ:

Figure F3. Elemental absorption—vitrified product, experiment CPAR 3.

Cursor: 0.000keV = 0

ROI (1) 9 440: 9.800



0.000

VFS = 4096 10.240

100 CPAR-4 / VIT.

SSQ

SEMI-QUANTITATIVE ANALYSIS: CPAR-4 / VIT.
EL NORM. K-RATIO

FE-K 0.68514 +- 0.00323
SI-K 0.05575 +- 0.00051
CA-K 0.22450 +- 0.00122
TI-K 0.02250 +- 0.00045
MG-K 0.01209 +- 0.00026

ZAF CORRECTION 20.00 KV 76.80 Degs

No. of Iterations 2

----	K	[Z]	[A]	[F]	[ZAF]	ATOM. %	WT. %
FE-K	0.685	1.034	1.016	1.000	1.051	56.46	67.45
SI-K	0.055	0.928	1.568	0.996	1.451	12.68	7.58 *
CA-K	0.224	0.945	1.050	0.967	0.961	23.69	20.21
TI-K	0.022	1.034	1.068	0.934	1.033	2.13	2.18
MG-K	0.012	0.919	2.485	0.998	2.281	5.05	2.58 *

* - High Absorbance

SSQ:

Figure F4. Elemental absorption—vitrified product, experiment CPAR 4.

Appendix G: CPAR Temperature Data - Plasma Gas Effect

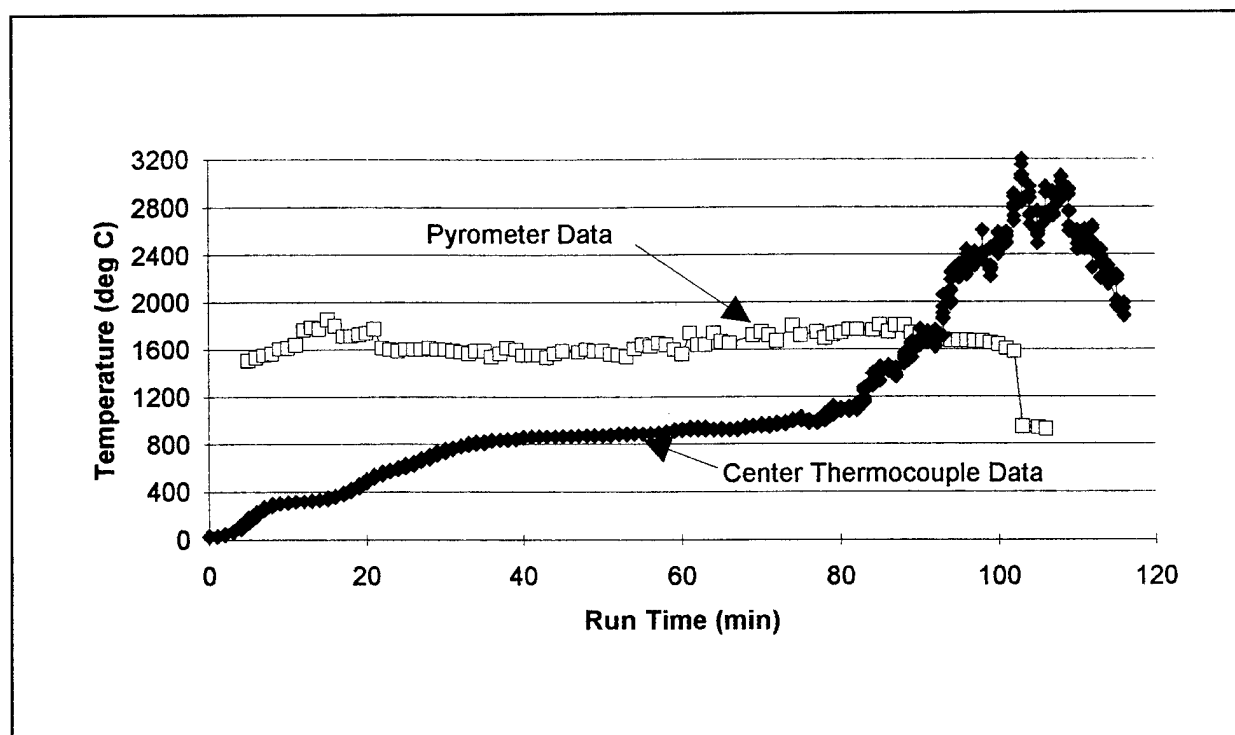


Figure G1. CPAR temperature data—plasma gas effect, experiment CPAR 1.

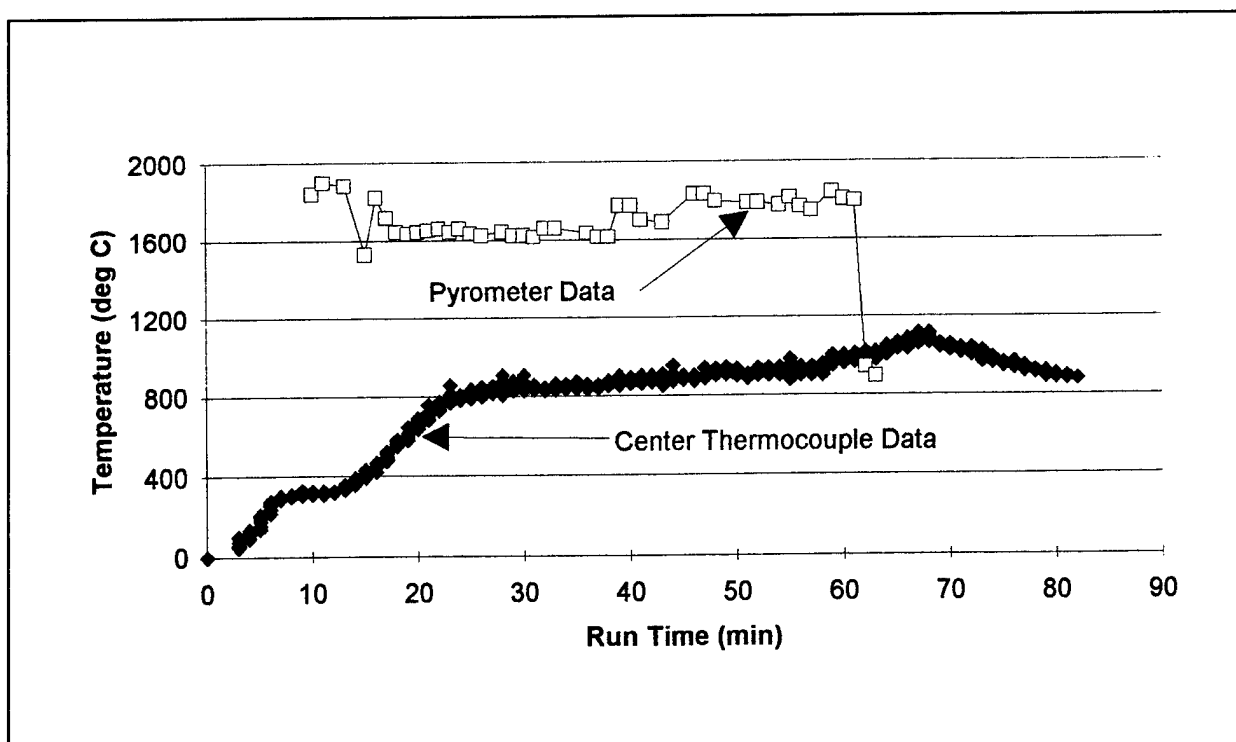


Figure G2. CPAR temperature data—plasma gas effect, experiment CPAR 2.

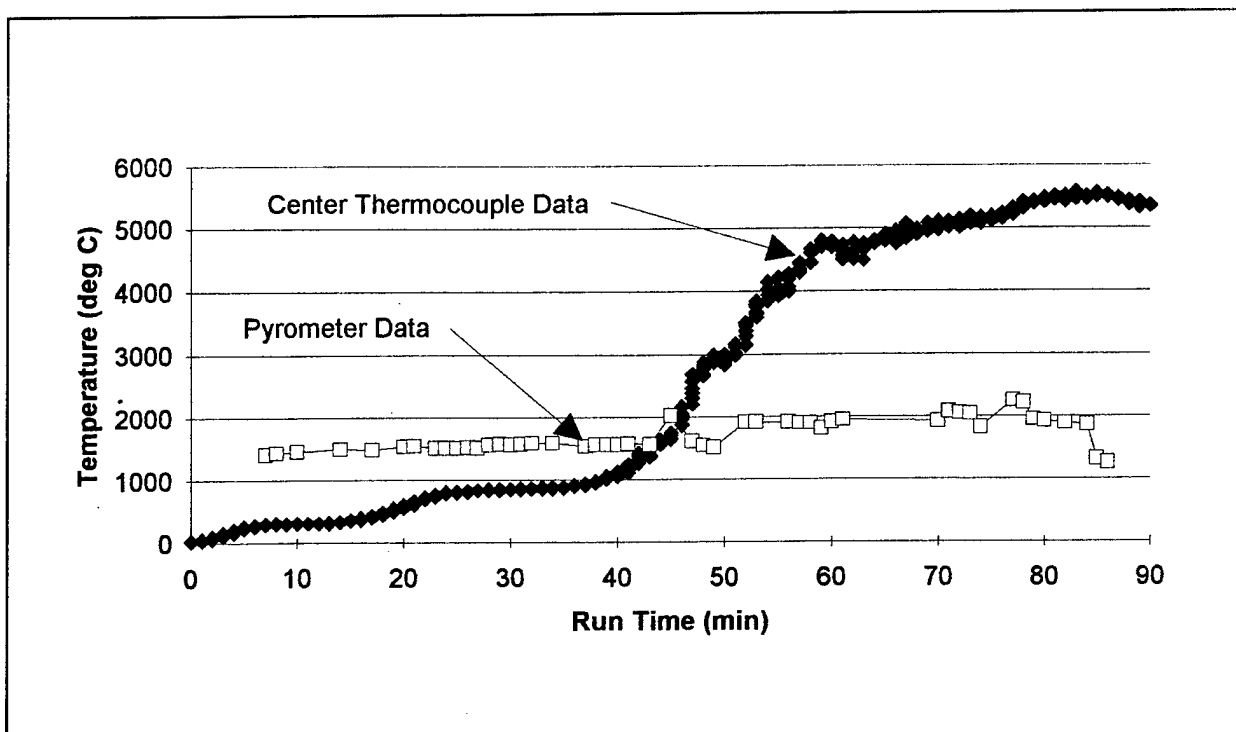


Figure G3. CPAR temperature data—plasma gas effect, experiment CPAR 3.

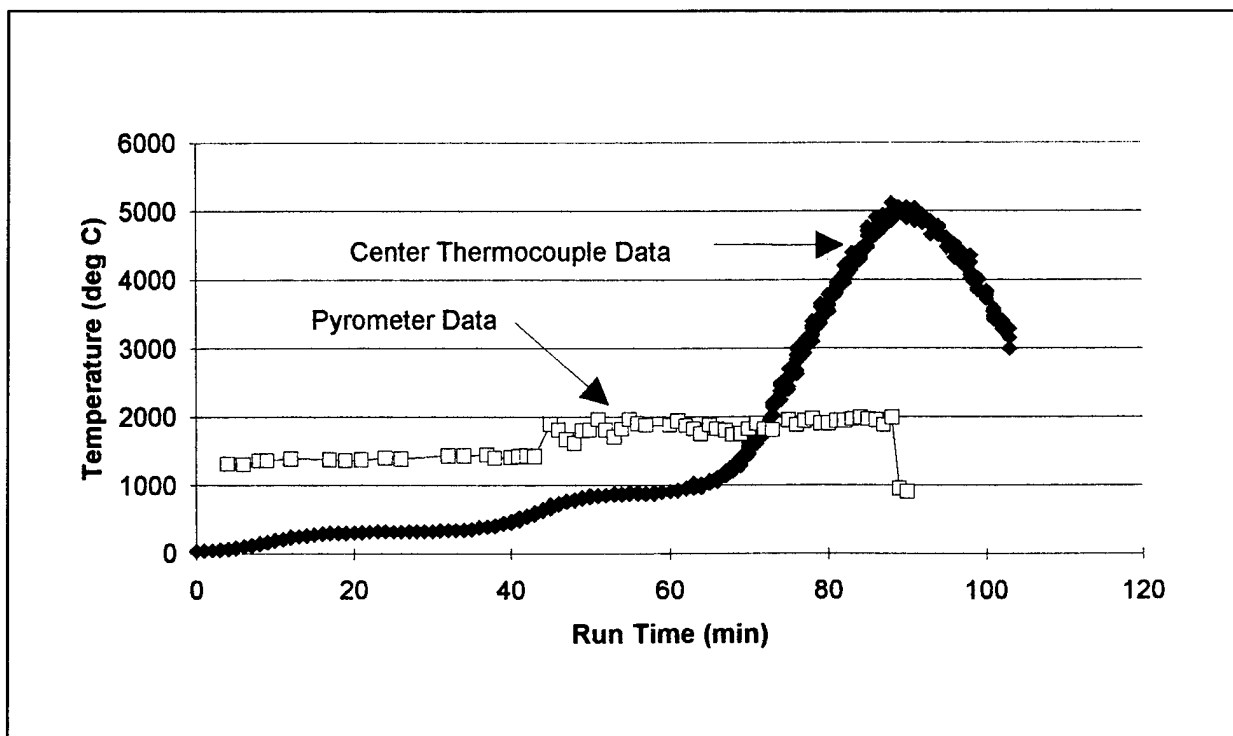


Figure G4. CPAR temperature data—plasma gas effect, experiment CPAR 4.

Appendix H: CPAR Thermocouple Data - Experiment Observations

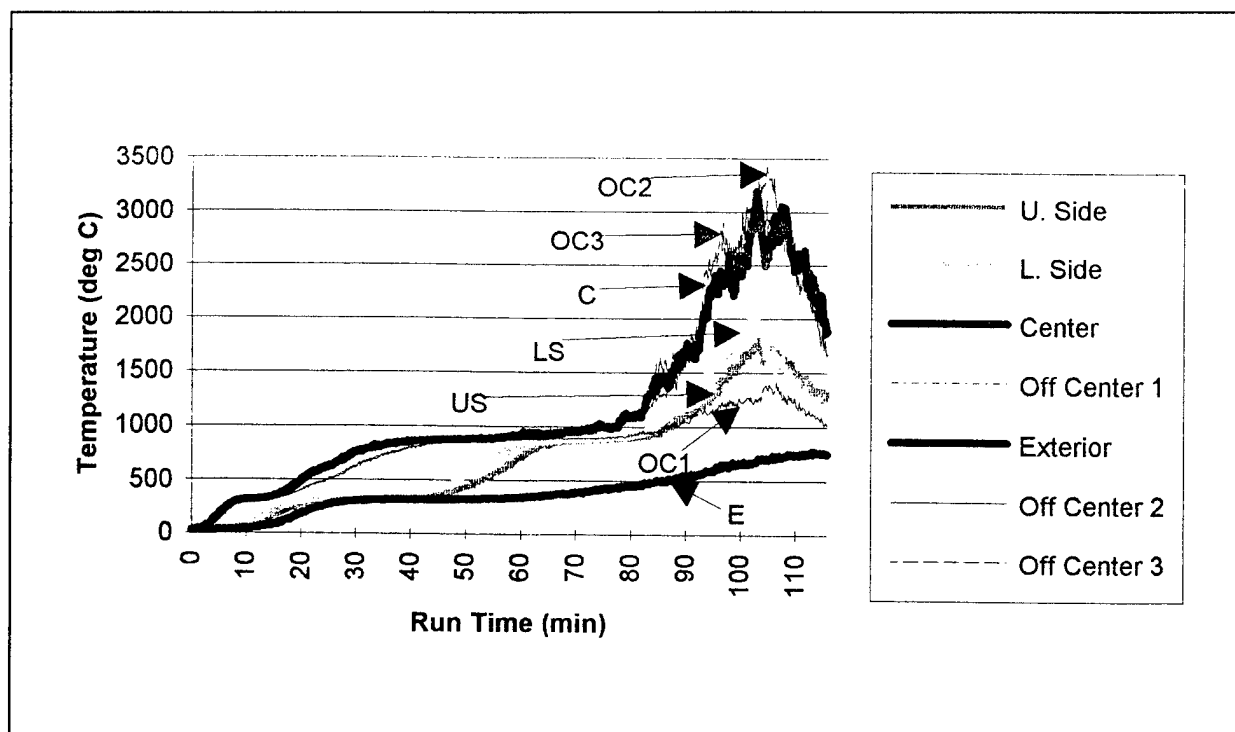


Figure H1. CPAR thermocouple data—experimental observations, experiment CPAR 1.

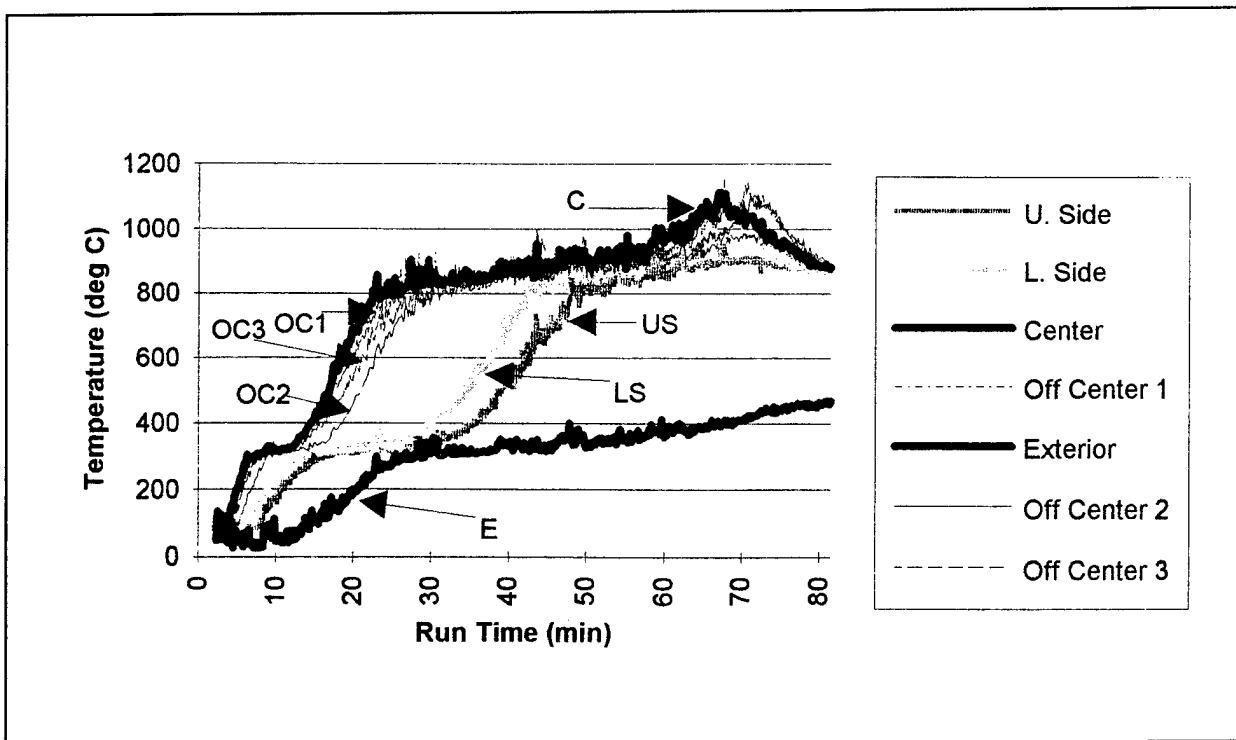


Figure H2. CPAR thermocouple data—experimental observations, experiment CPAR 2.

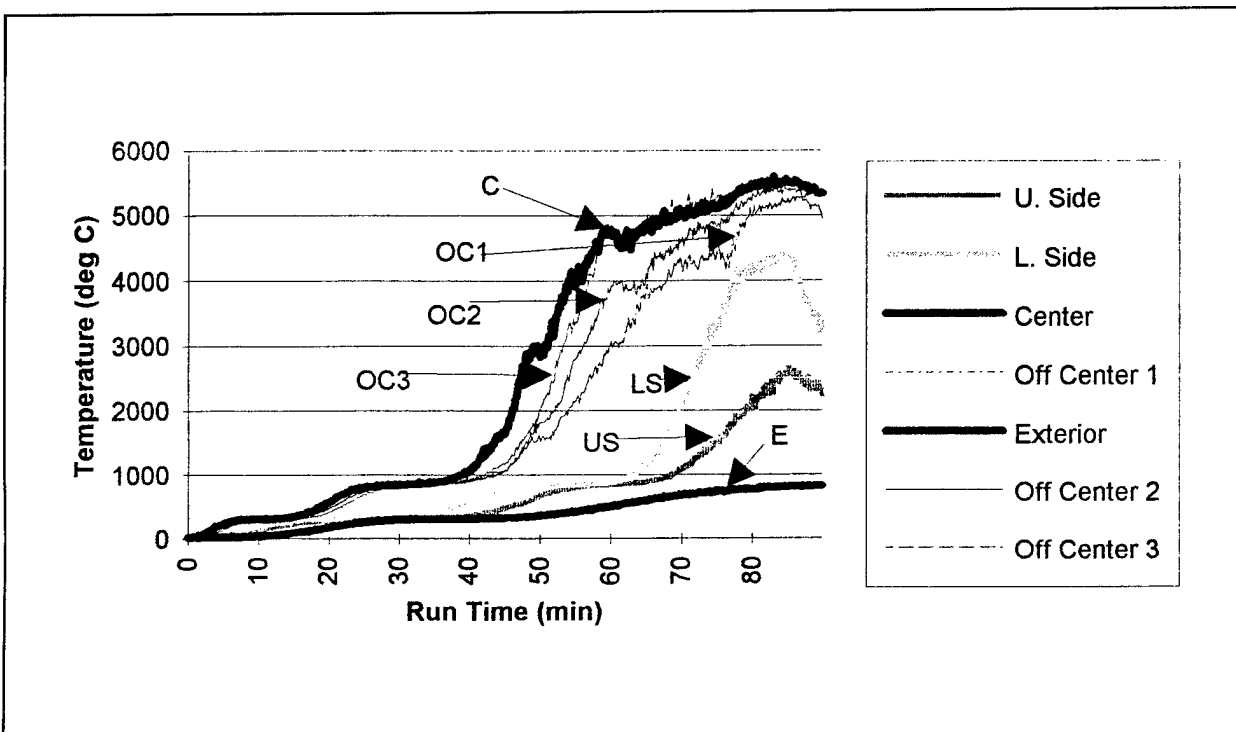


Figure H3. CPAR thermocouple data—experimental observations, experiment CPAR 3.

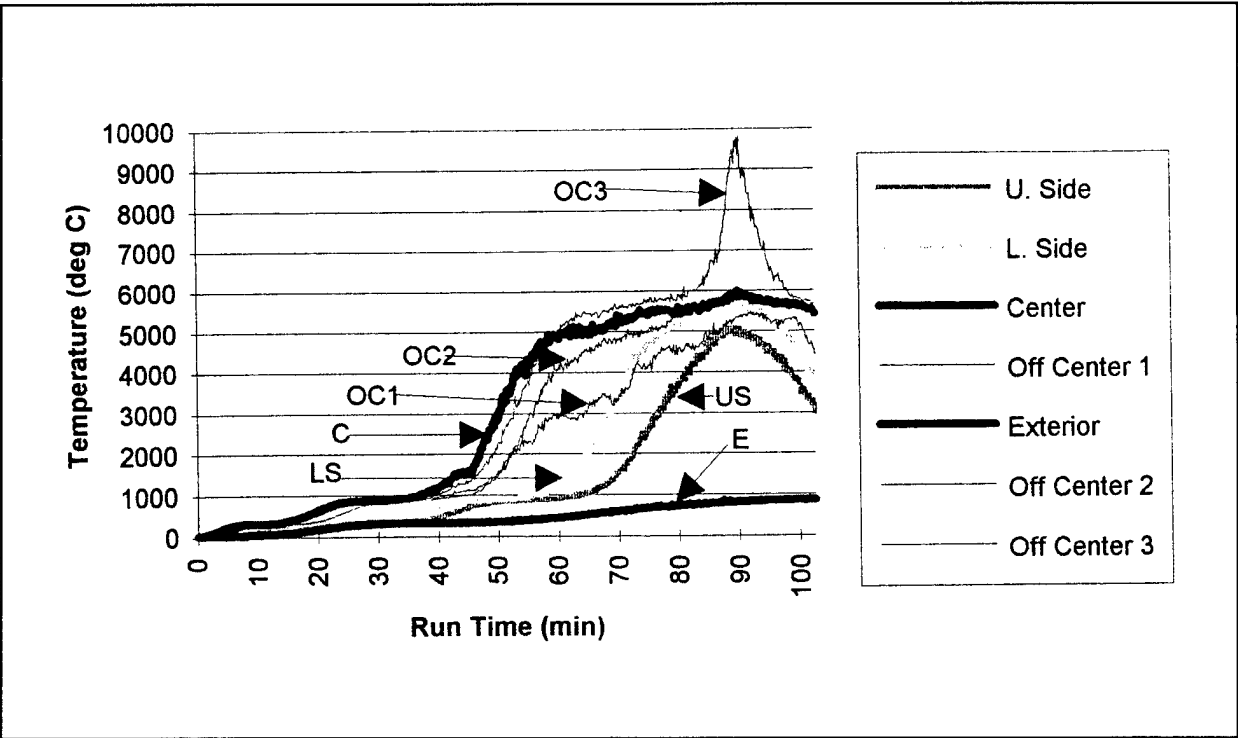


Figure H4. CPAR thermocouple data—experimental observations, experiment CPAR 4.

Appendix I: ACM Decomposition Photographs

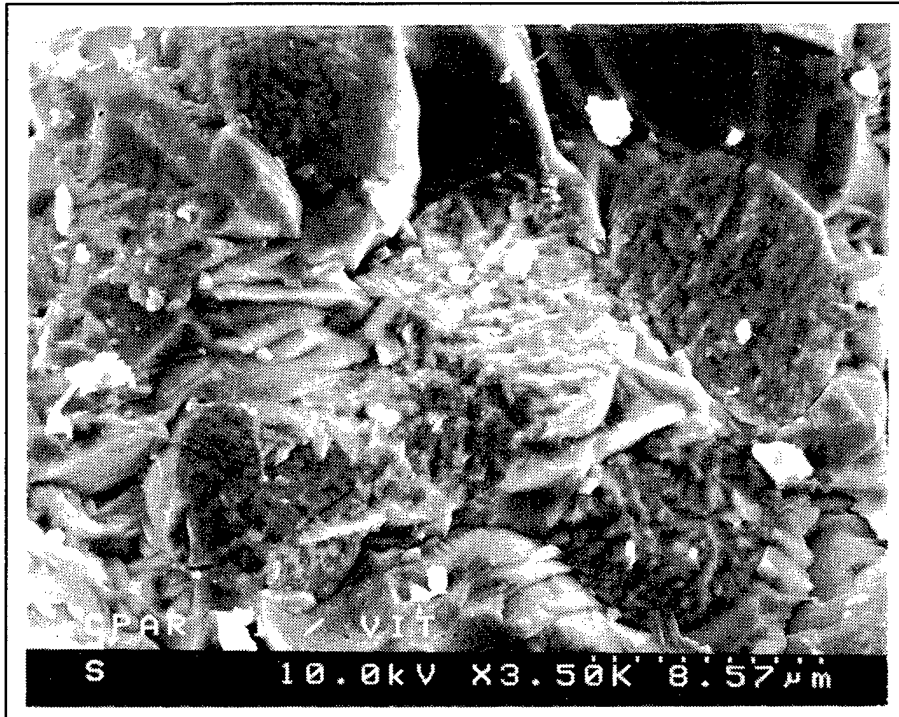


Figure I1. ACM decomposition—vitrified product, experiment CPAR 1.

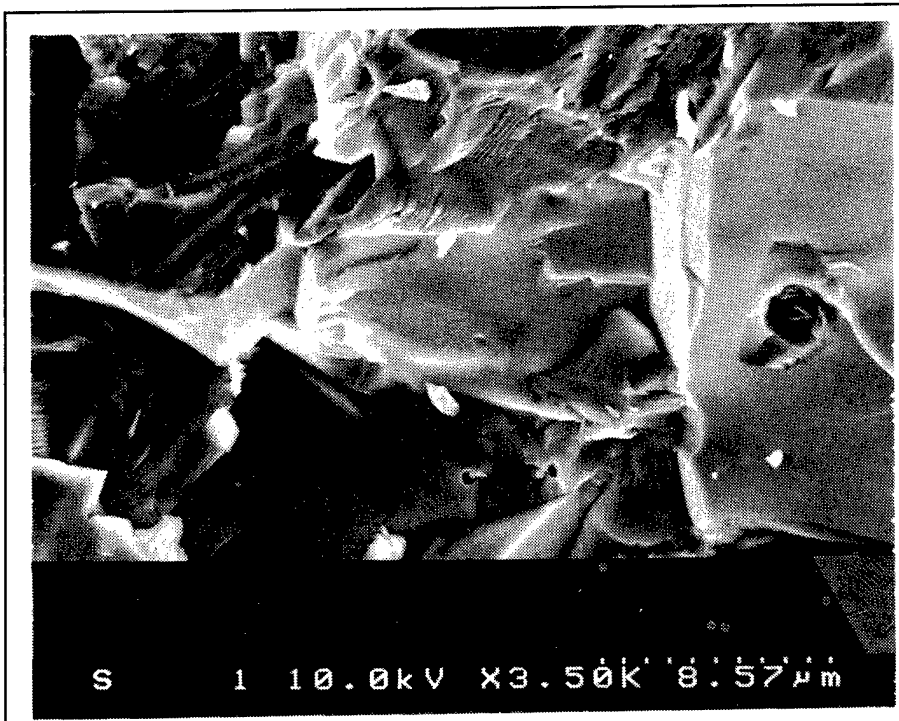


Figure I2. ACM decomposition—vitrified product, experiment CPAR 2.

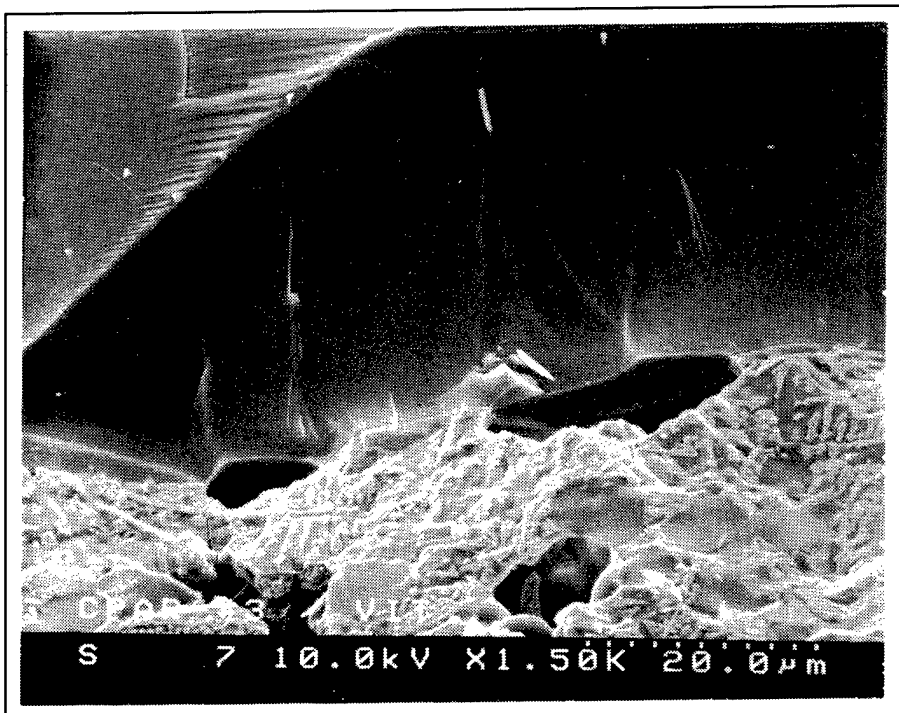


Figure I3. ACM decomposition—vitrified product, experiment CPAR 3

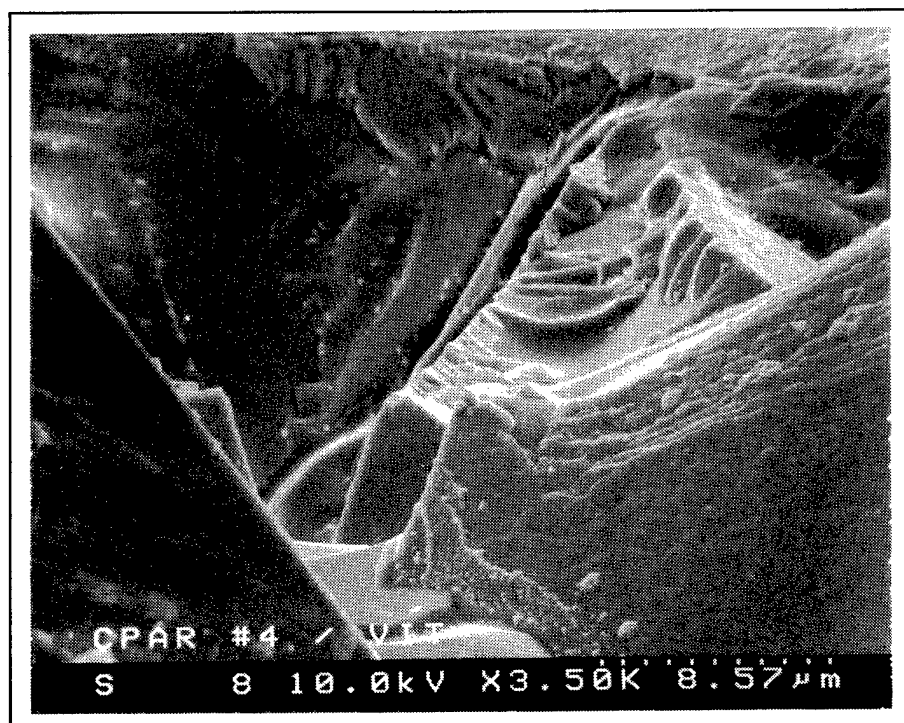


Figure 14. ACM decomposition—vitrified product, experiment CPAR 4

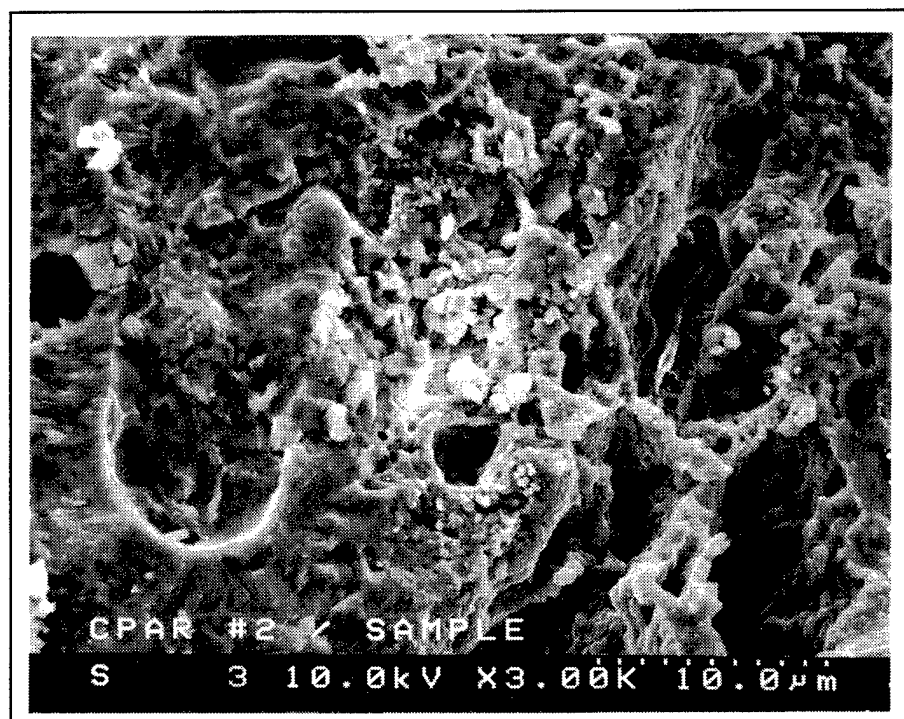


Figure 15. Decomposed product, experiment CPAR 2, sample 1.

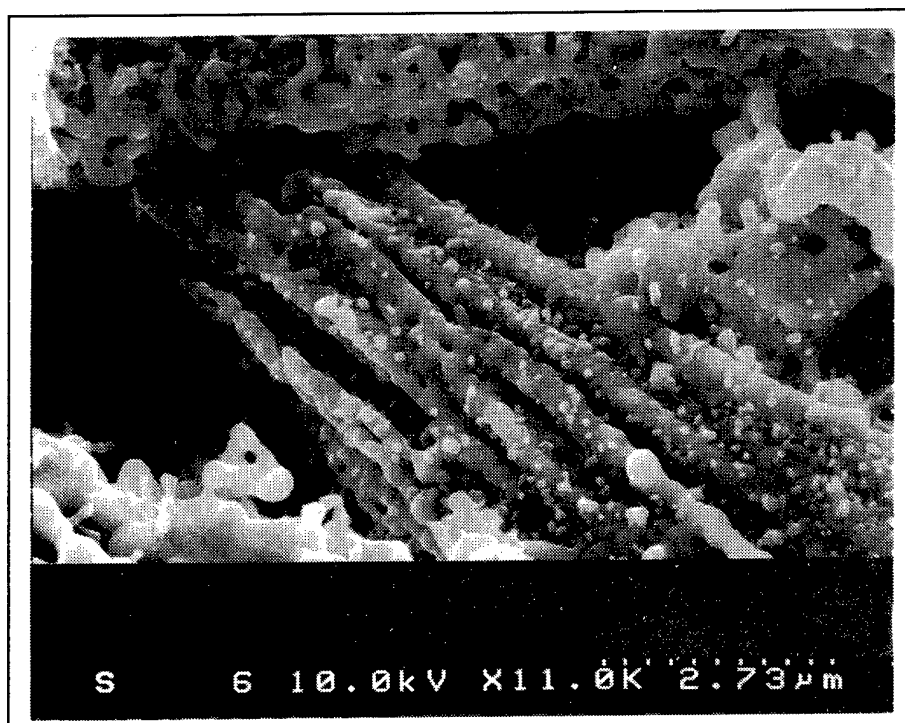


Figure I6. Decomposed product, experiment CPAR 2, sample 2.

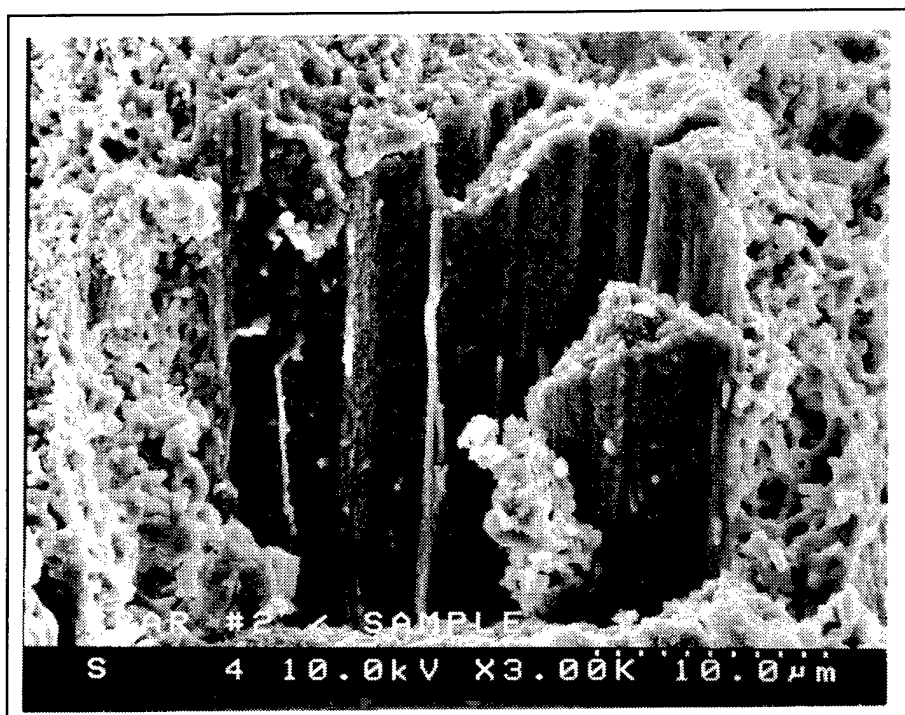


Figure I7. Decomposed product, experiment CPAR 2, sample 3.

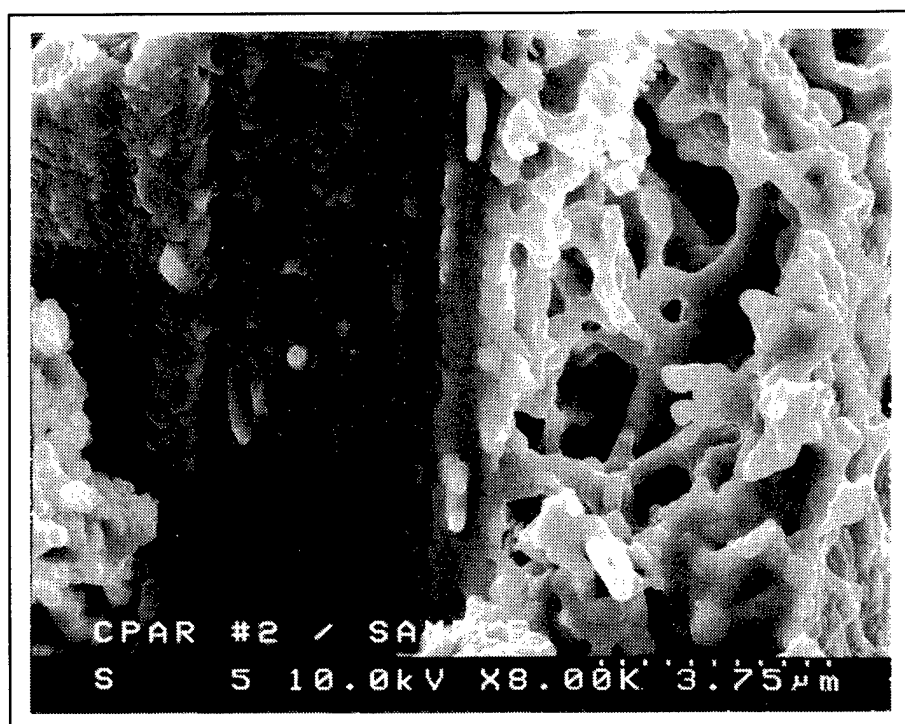


Figure I8. Decomposed product, experiment CPAR 2, sample 4.

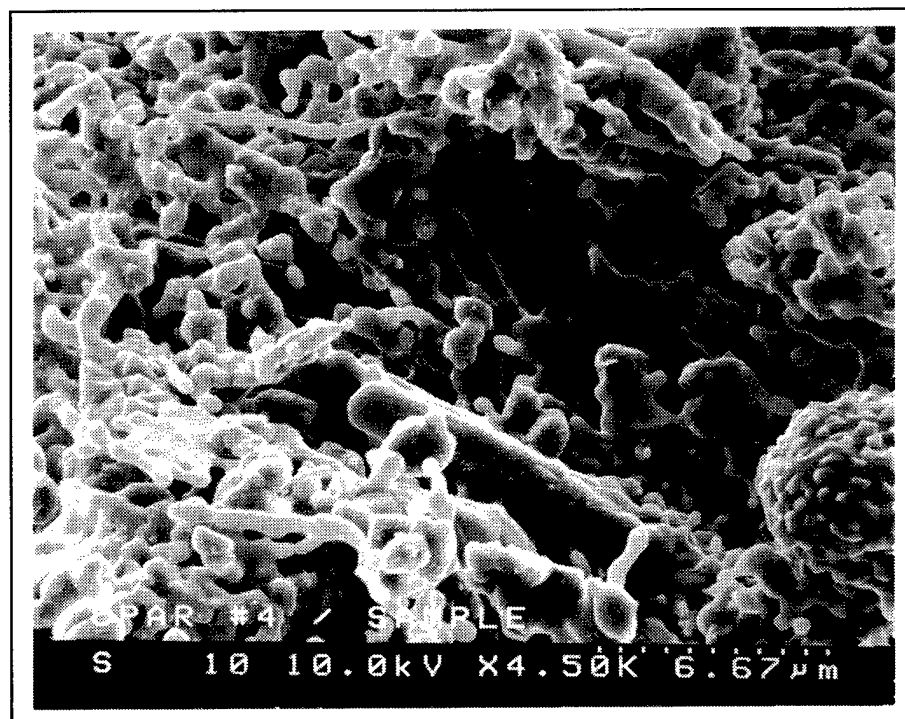


Figure I9. Decomposed product, experiment CPAR 4, sample 1.

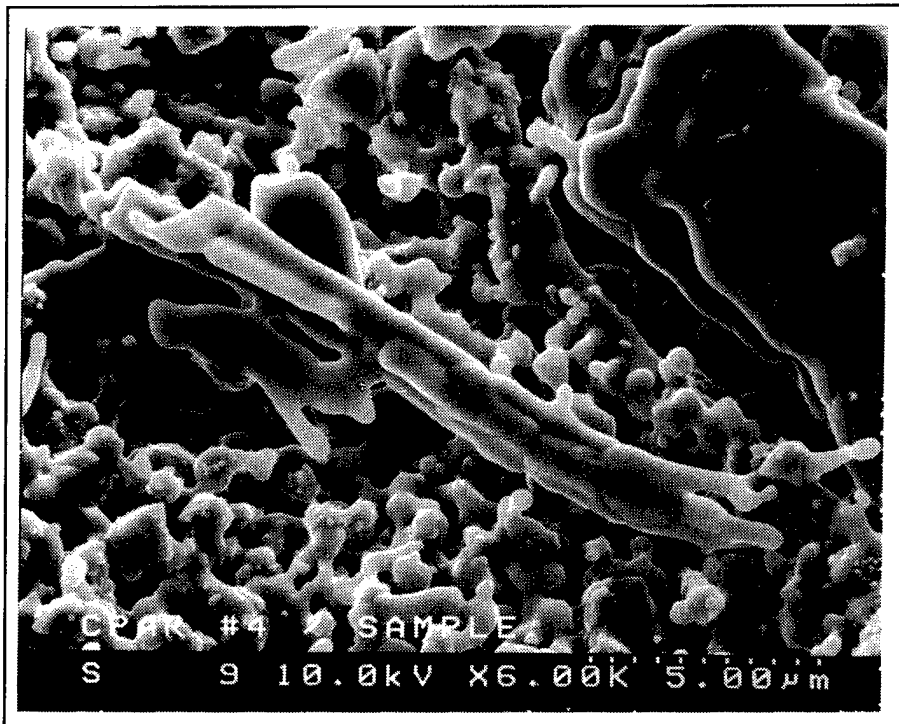


Figure I10. Decomposed product, experiment CPAR 4, sample 2.

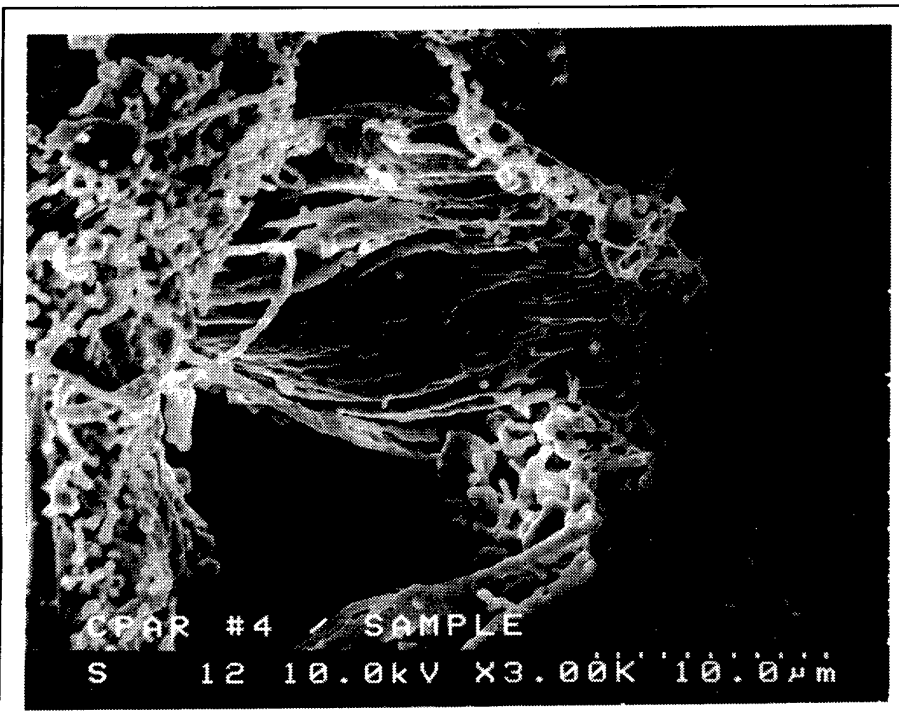


Figure I11. Decomposed product, experiment CPAR 4, sample 3.

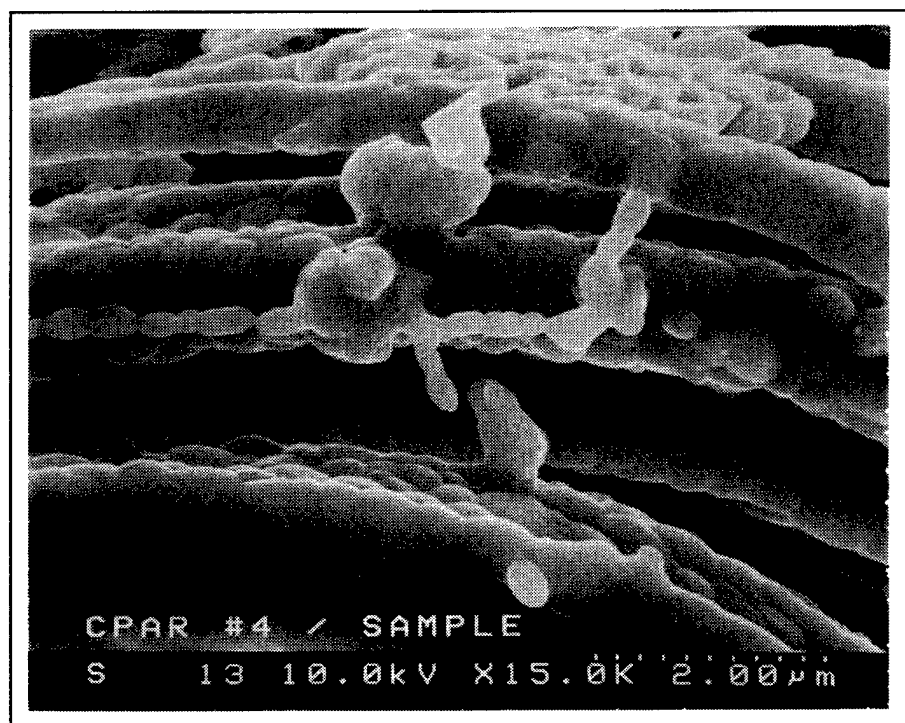


Figure I12. Decomposed product, experiment CPAR 4, sample 4.

Appendix J: Plasma Torch Power and Pressure Data

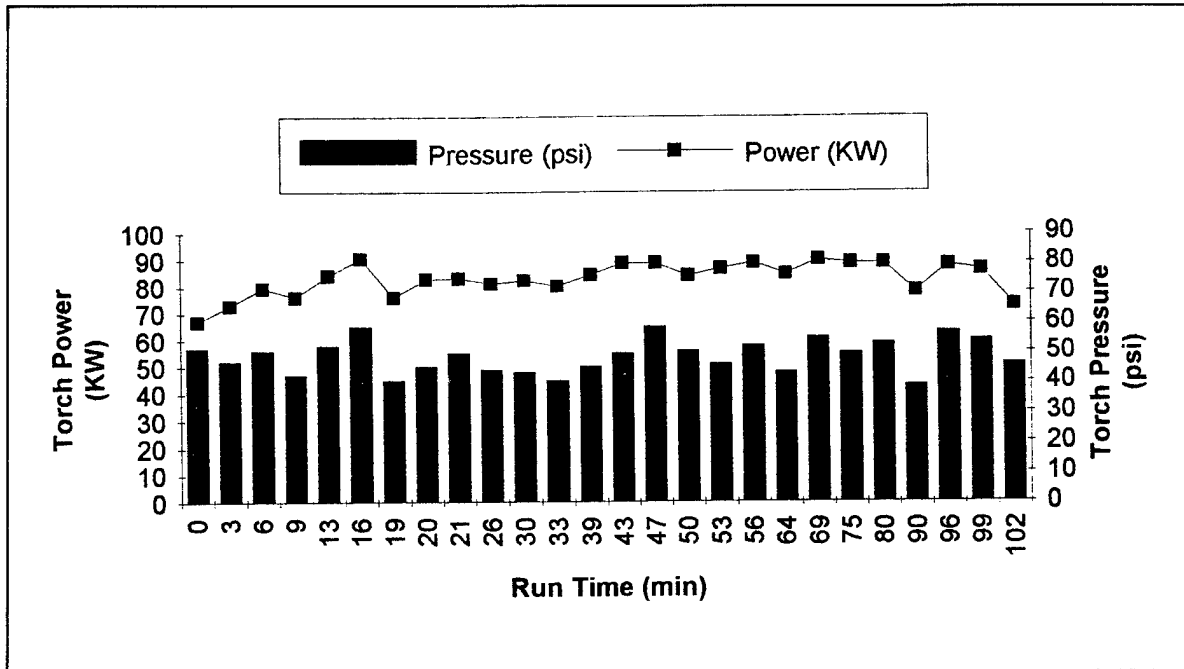


Figure J1. Plasma torch power and pressure data, experiment CPAR 1.

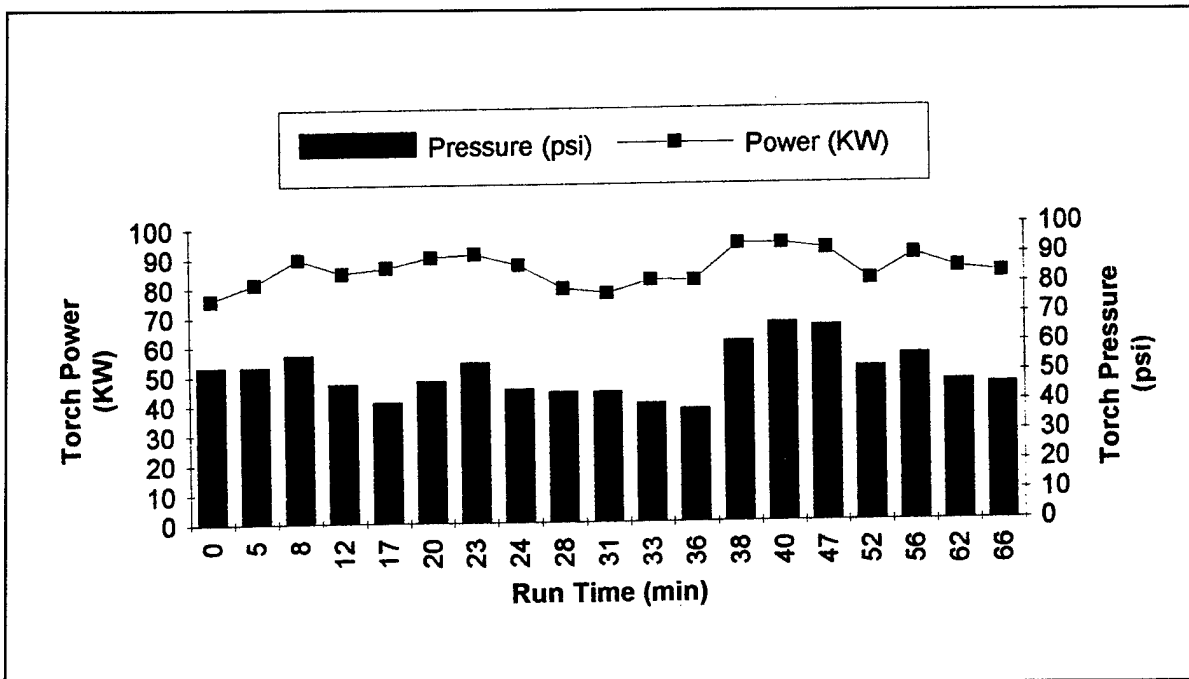


Figure J2. Plasma torch power and pressure data, experiment CPAR 2.

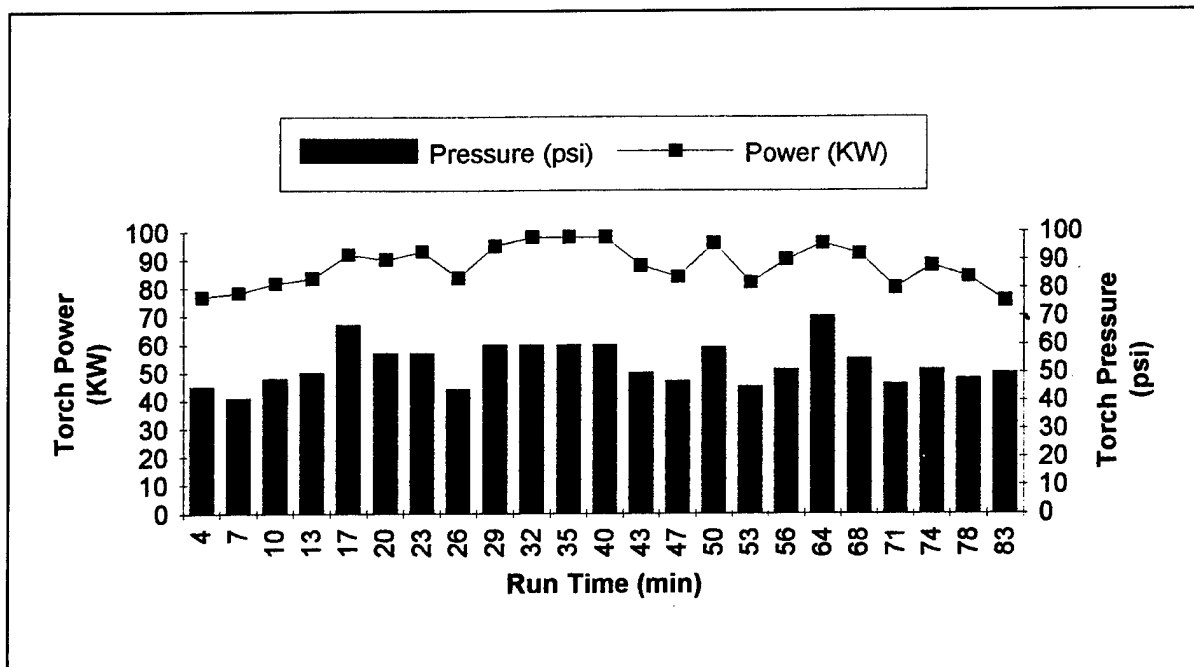


Figure J3. Plasma torch power and pressure data, experiment CPAR 3.

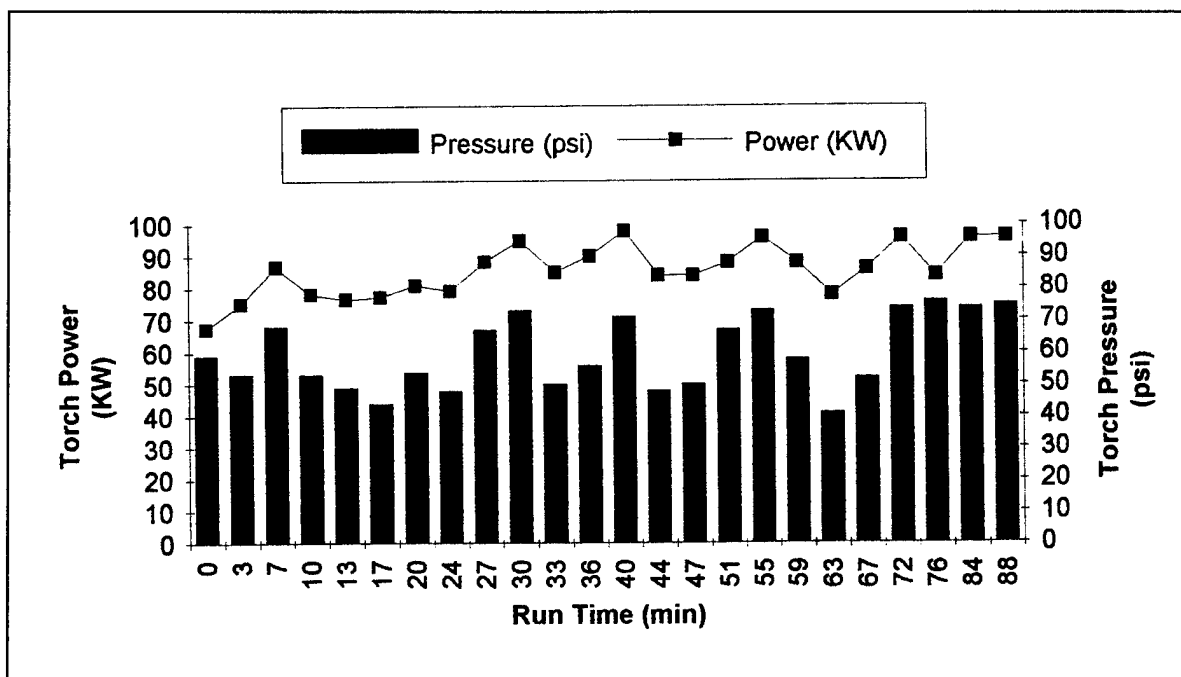


Figure J4. Plasma torch power and pressure data, experiment CPAR 4.

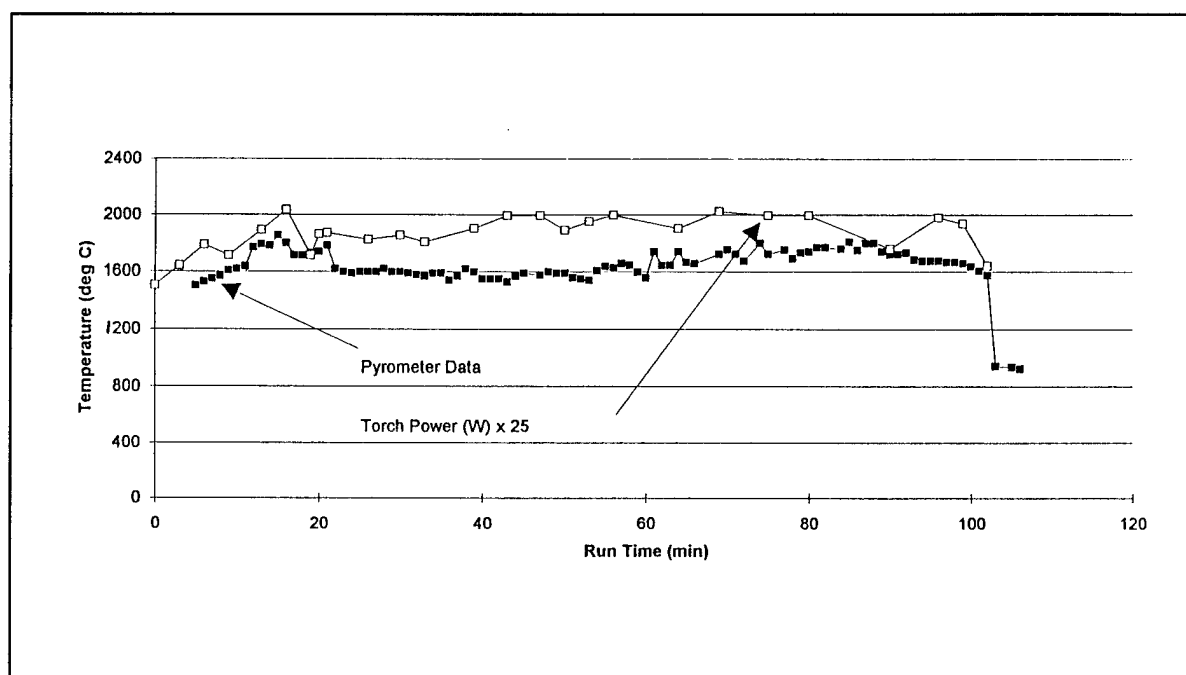


Figure J5. Pyrometer/power data, experiment CPAR 1.

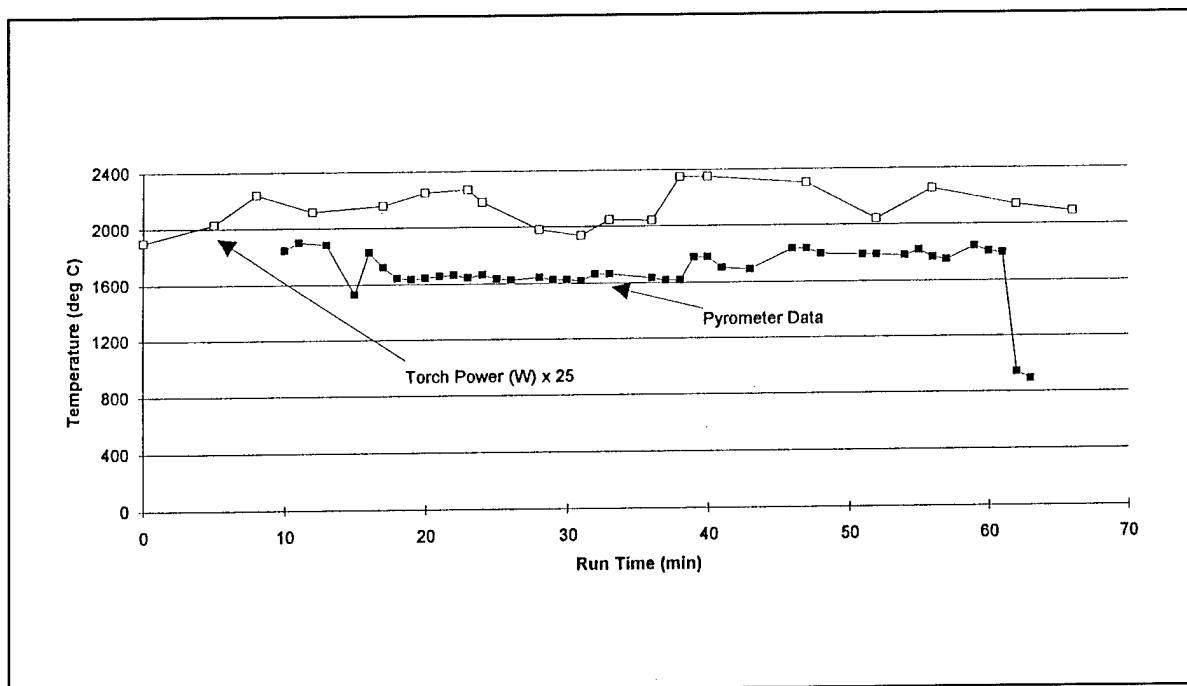


Figure J6. Pyrometer/power data, experiment CPAR 2.

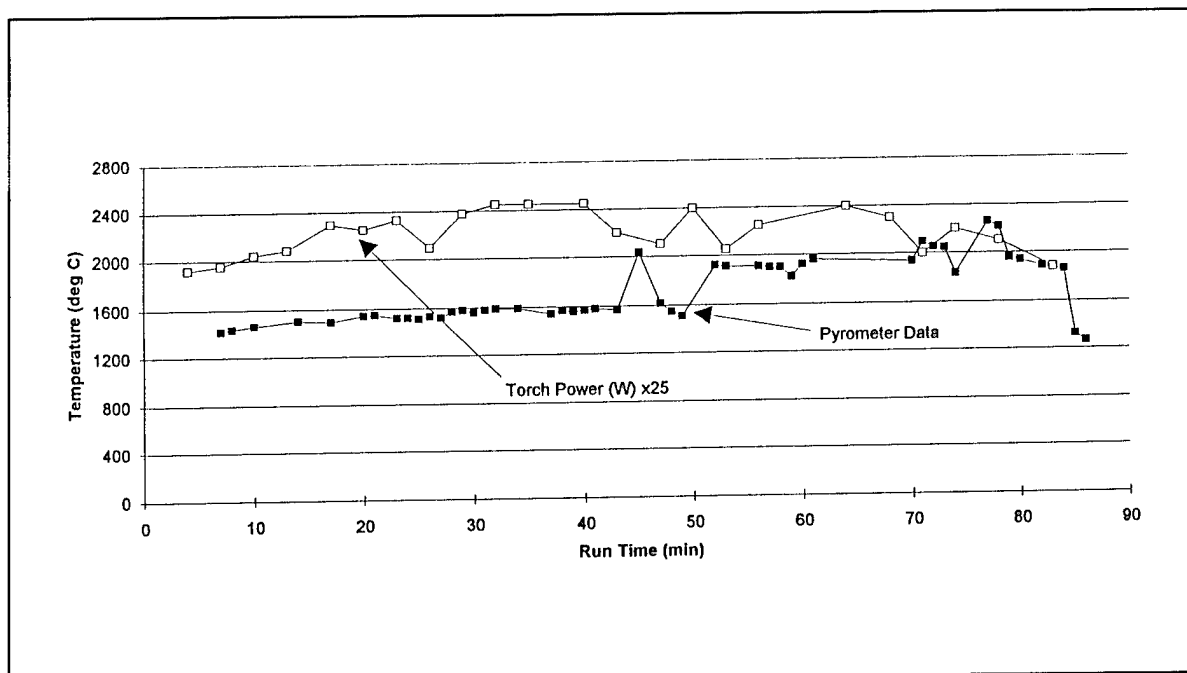


Figure J7. Pyrometer/power data, experiment CPAR 3.

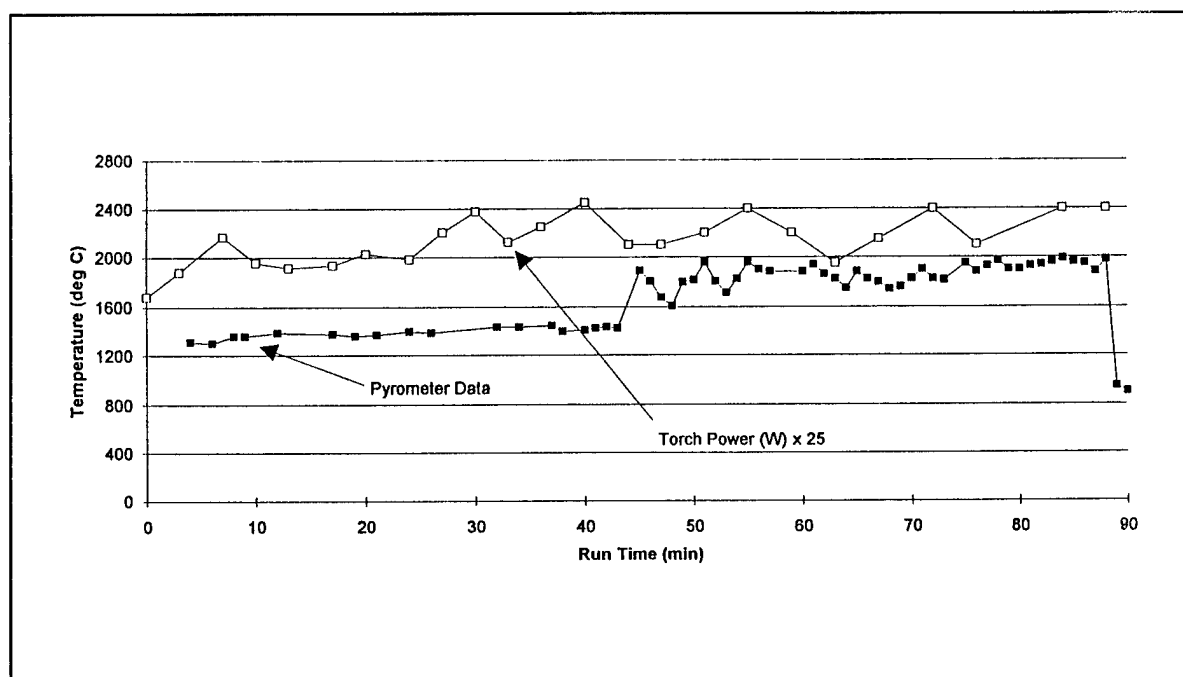
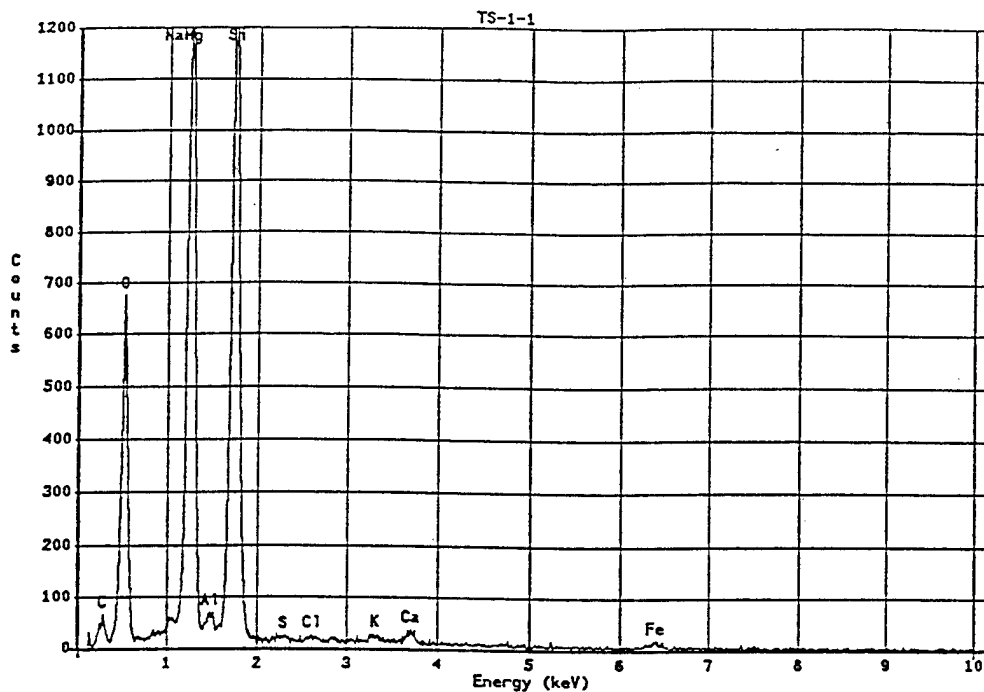


Figure J8. Pyrometer/power data, experiment CPAR 4.

Appendix K: RMA - ACM Sample Locations

TEST RUN	PKG #	DESCRIPTION	CANISTER IDENTIFICATION	SAMPLE WEIGHT	TOTAL WEIGHT	TEST TOTAL
Test Sample 1 5/6/94	#13	Bldg 516, 2nd floor mag block tank covering	1. TS1P13A 2. TS1P13B 3. TS1P13C 4. TS1P13D 5. TS1P13E	1. 194g 2. 257g 3. 330g 4. 111g 5. 140g	1. 324g 2. 417g 3. 454g 4. 235g 5. 261g	1693g
Test Sample 2 5/10/94	#3 #4 #8 #13	2nd floor west center pipeline TSI #514 015 2nd floor west wall pipeline TSI air cell 3rd floor northwest TSI tank pipeline lower exposed piping Bldg 516, 2nd floor mag block tank covering	1. TS2P3AP4AP8A 2. TS2P3BP4BP8B 3. TS2P3CP4CP8C 4. TS2P3DP4DP8D 5. TS2P3EP4EP8E 6. TS2P3FP4F 7. TS2P3GP4GP13F 8. TS2P3HP4HP13G 9. TS2P3IP13H 10. TS2P3J	1. 264g 2. 213g 3. 178g 4. 218g 5. 222g 6. 104g 7. 174g 8. 251g 9. 198g 10. 74g	1. 433g 2. 349g 3. 304g 4. 352g 5. 424g 6. 264g 7. 312g 8. 321g 9. 321g 10. 204g	3284g
Test Sample 3 5/12/94	#5 #9	2nd floor northwest tank top TSI mag block 3rd floor southeast mag block tank	1. TS3P5AP9A 2. TS3P5BP9B 3. TS3P5CP9C 4. TS3P5DP9D 5. TS3P5EP9E	1. 300g 2. 283g 3. 324g 4. 233g 5. 329g	1. 447g 2. 410g 3. 453g 4. 403g 5. 447g	2160g
Test Sample 4 5/16/94	#7 #13	2nd floor southeast room sealer around tank thou floors Bldg 516, 2nd floor mag block tank covering	1. TS4P7A 2. TS4P7B 3. TS4P7CP13I	1. 672g 2. 710g 3. 323g	1. 825g 2. 821g 3. 444g	2090g
Full Test 1 5/18/94	#1 #6 #11 #12	tank room floor, a piece of TSI where roof is missing 2nd floor northeast room TSI tank covering 4th floor north tank warp from floor 1st floor southwest wall piping	1. FT1P1AP6AP11AP12A 2. FT1P1BP6BP11BP12B 3. FT1P1CP6CP11CP12C	1. 373g 2. 260g 3. 322g	1. 520g 2. 375g 3. 432g	1327g
Full Test 2 5/20/94	#2 #13	tank floor room, a piece of transite roof Bldg 516, 2nd floor mag block tank covering	1. FT2P2A 2. FT2P2BP13J	1. 802g 2. 343g	1. 885g 2. 491g	1376g
Full Test 3 5/23/94	#10 #14 #13	4th floor east wall mastic bldg 328, east doorway black mastic spray on Bldg 516, 2nd floor mag block tank covering	1. FT3P10AP14A 2. FT3P10BP14B 3. FT3P10C 4. FT3P5FP10DP13K	1. 549g 2. 574g 3. 582g 4. 304g	1. 686g 2. 696g 3. 713g 4. 392g	2487g
Full Test 4 5/25/94	#15	pipeline "F" "14" steamline area #2	1. FT4P15A 2. FT4P15B 3. FT4P15C	1. 315g 2. 287g 3. 283g	1. 426g 2. 422g 3. 424g	1272g

Appendix L: RMA Electron Absorption Data



Refit Na-K' Na-K"
 Refit Al-K' Al-K" S -K" Cl-K' Cl-K" K -K' K -K" Ca-K" Fe-K' Fe-K"

Wed May 11 11:11:44 1994

TS-1-1

Chi-sqd = 0.82 Livetime = 100.0 Sec.

Standardless Analysis

Element	Relative k-ratio	Error (1-Sigma)	Net Counts	Error (1-Sigma)
Na-K	0.00468 +/-	0.00217	97 +/-	45
Mg-K	0.41539 +/-	0.00508	12829 +/-	157
Al-K	0.00936 +/-	0.00202	270 +/-	58
Si-K	0.51159 +/-	0.00537	14000 +/-	147
S -K	0.00445 +/-	0.00140	93 +/-	29
Cl-K	0.00698 +/-	0.00138	138 +/-	27
K -K	0.00763 +/-	0.00161	134 +/-	28
Ca-K	0.01902 +/-	0.00197	289 +/-	30
Fe-K	0.02089 +/-	0.00385	163 +/-	30

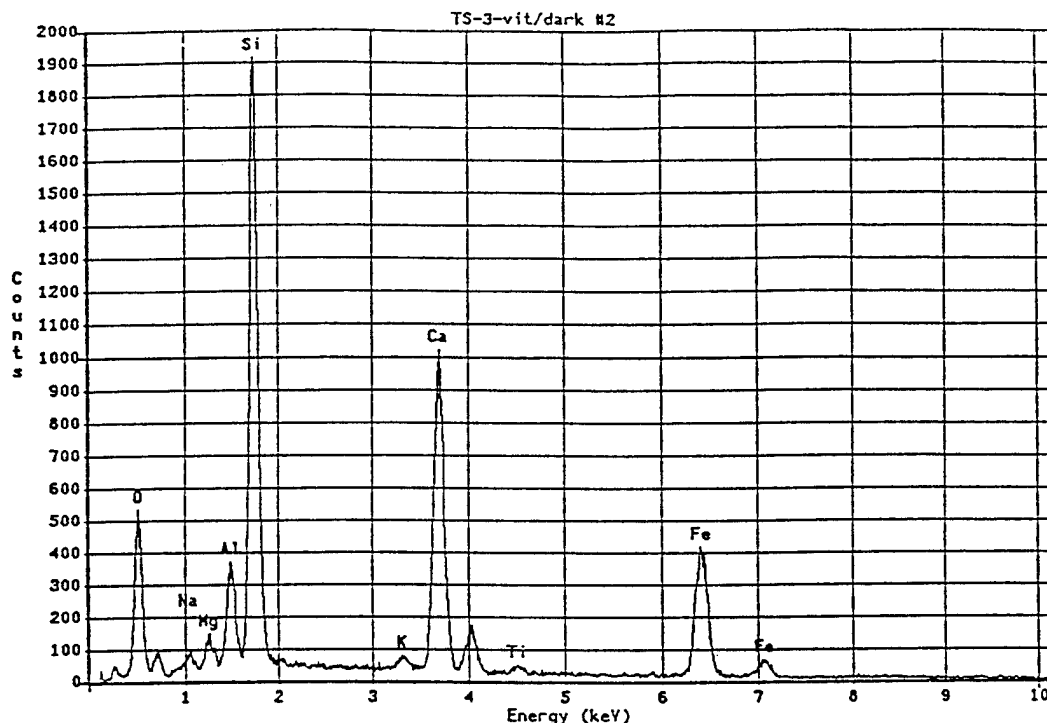
Adjustment Factors

	K	L	M
Z-Balance:	0.0000	0.0000	0.0000
Shell:	1.0000	1.0000	1.0000

PROZA Correction Acc.Volt.= 20 kV Take-off Angle=42.11 deg Tilt = 30 deg
 Number of Iterations = 4

Element	k-ratio (calc.)	ZAF	Atom %	Element	Wt % Wt % Err. (1-Sigma)
Na-K	0.00349	1.348	0.55	Na-K	0.47 +/- 0.22
Mg-K	0.31009	1.151	39.74	Mg-K	35.70 +/- 0.44
Al-K	0.00699	1.779	1.25	Al-K	1.24 +/- 0.27
Si-K	0.38191	1.487	54.72	Si-K	56.80 +/- 0.60
S -K	0.00333	1.749	0.49	S -K	0.58 +/- 0.18
Cl-K	0.00521	1.590	0.63	Cl-K	0.83 +/- 0.16
K -K	0.00570	1.323	0.52	K -K	0.75 +/- 0.16
Ca-K	0.01420	1.230	1.18	Ca-K	1.75 +/- 0.18
Fe-K	0.01560	1.206	0.91	Fe-K	1.88 +/- 0.35
Total			100.00	Total	100.00

Figure L1. RMA electron absorption data for Figure 9.



Refit K-K' K-K'' Ti-K' Ti-K''
 Refit Al-K' Si-K'' Ca-K' Ca-K'' Mg-K' Na-K' Ti-K

Tue May 17 12:02:11 1994

TS-3-vit/dark #1

Chi-sqd = 9.70 Livetime = 100.0 Sec.

Standardless Analysis

Element	Relative k-ratio	Error (1-Sigma)	Net Counts	Error (1-Sigma)
Al-K	0.00283 +/-	0.00074	331 +/-	86
Si-K	0.00109 +/-	0.00041	122 +/-	45
Ca-K	0.00497 +/-	0.00085	307 +/-	52
Fe-K	0.97891 +/-	0.00953	30918 +/-	301
Mg-K	0.00711 +/-	0.00062	890 +/-	78
Na-K	0.00497 +/-	0.00069	418 +/-	58
K-K	0.00011 +/-	0.00068	9 +/-	53
Ti-K	0.00000 +/-	0.00001	0 +/-	0

Adjustment Factors

	K	L	M
Z-Balance:	0.0000	0.0000	0.0000
Shell:	1.0000	1.0000	1.0000

PROZA Correction Acc.Volt.= 20 kV Take-off Angle=42.11 deg Tilt = 30 deg
 Number of Iterations = 4

Element	k-ratio (calc.)	ZAF	Atom %	Element	Wt % Err. (1-Sigma)
Al-K	0.00263	2.437	1.24	0.64	+/- 0.17
Si-K	0.00101	1.815	0.34	0.18	+/- 0.07
Ca-K	0.00462	0.968	0.58	0.45	+/- 0.08
Fe-K	0.90896	1.037	88.00	94.27	+/- 0.92
Mg-K	0.00660	3.269	4.63	2.16	+/- 0.19
Na-K	0.00462	4.961	5.19	2.29	+/- 0.32
K-K	0.00011	1.037	0.01	0.01	+/- 0.07
Ti-K	0.00000	0.940	0.00	0.00	+/- 0.00
Total			100.00	100.00	

Figure L2. RMA electron absorption data for Figure 10.

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412th Base Support Battalion 09630

ATTN: Unit 31401

Frankfurt Base Support Battalion

ATTN: Unit 25727 09242

CMTC Hohenfels 09173

ATTN: AETTH-DEH

Mainz Germany 09185

ATTN: BSB-MZ-B

21st Support Command

ATTN: DEH (10)

US Army Berlin

ATTN: AEBA-EH 09235

ATTN: AEBA-EN 09235

SETAP

ATTN: AESE-EN-D 09613

ATTN: AESE-EN 09630

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